The optimisation of the digging sequence of a dragline

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Abstract

The dragline’s repositioning is a large component of its operation. This relates to the dragline’s walking sequence, that is, to where the dragline should stand, dig and dump to, and to when and where it moves. A trade-off exists as to whether to remain digging at a particular location or whether to reposition in order to achieve more favourable dig-conditions or swing-angles. Since the dragline’s repositioning requires a major loss of productive cycling-hours, more feasible, dig and swing conditions are essential in order to achieve a higher productivity.

The dragline’s operators or supervisors currently make many repositioning decisions during its operation. This is still very costly in terms of time and operation, although different repositioning strategies and various computer software programs for the comparison of multiple scenarios of the mine plan are available. Feedback to the operator can indicate the ideal time for the relocation of the dragline and can thus enable a large reduction in the cost of repositioning actions.

Previous research has analysed this trade-off by developing a cost function per horizontal bucket-foot of movement. It has also recommended the repositioning of the dragline by the operators if the expected cost of continuing to dig at a certain position exceeds the delay and dig-costs that are associated with a repositioning. This approach doesn’t, however, consider the cost penalties, which are associated with hoist-limited cycles.

An algorithm has been developed in this research for advising the operators on how to improve the dragline dig-sequences. Dragline, repositioning information was analysed after collecting cycle-data over a representative, one-year period. A cost model has been derived from the collected data to monitor the operator performance at each stage of the excavation sequence. Repositioning suggestions and dig-sequence improvements, which are based on the current master mine-plan and operation, can thus be provided using a search, heuristic, optimisation model.

There are benefits of providing this repositioning information and this optimised dig-sequence capability to the dragline operators. The dragline’s utilisation and productivity will be enhanced as a result of making the operators aware of the consequence of non-optimal
dig-sequences. A reduction in the dragline’s energy consumption will be a potential consequence of decreasing the incidence of hoist-limited cycles. Its asset life can also be extended since fewer, hoist-limited cycles will minimise boom and gearbox stresses and will also enhance the life of the components.
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Chapter 1 Introduction

1.1 Background

Dragline performance monitors have evolved since the 1980’s from closed systems that employed proprietary databases and communications download-links, to the current systems, which provide an open access to data and to software applications. Vynne (2008) has recently reviewed the capabilities of current, dragline, performance-monitoring systems. This review focused on the integration of structural and performance monitoring-systems, and concluded that significant, dragline productivity-increases can be achieved without increasing its maintenance costs and without causing its structural members to fail. The Pegasys monitoring system, which is manufactured and supported by Mineware Pty Ltd, is typical of this latter class of monitoring systems. Pegasys dragline-monitors are currently in operation on the majority of Australian draglines that are owned by BMA and Westfarmers Resources’, as well as, on a number of draglines in South Africa and America.

Many researchers, when trying to reveal valuable insights into dragline operations, have conducted analyses of dragline monitoring-data. Thornton (2001) developed some appropriate statistical techniques for interpreting the large quantity of data, which is captured from dragline performance-monitors. This researcher investigated the use of data-clustering techniques and statistical-process controls (SPC) for detecting unplanned changes in operating conditions. Hettinger, Lumley and Graham (1999) also provided a set of tools for processing the dragline’s performance data by introducing the concepts of ‘comparative benchmarking’ and of ‘specific functional analysis’. These have helped to determine cause-and-effect relationships and to provide continuous, improvement opportunities for the dragline operations.

McInnes, Meehan and McDonald (2005) of CRCMining aimed to develop fatigue damage indicators for dragline booms as a function of swing speeds and payload. These projects relied on strain-gauge information from the key points of the dragline’s boom plus dynamic models of boom lattice behaviour (McInnes et al. 2005).
Also associated with the interpretation of monitoring data, the ultimate goal of the dragline’s operation is to maximise the coal’s exposure rate whilst minimising its unit cost. Weber (1990) also revealed the basic rules of mine planning and operation in his study, which were to:

- Move the minimum quantity of material
- Move materials in the shortest, possible distance
- Move materials with the minimum amount of equipment
- Move materials with the minimum number of people
- Move materials in the shortest, possible time

Draglines are the most expensive piece of excavating equipment at the mine site and it is important that they are operated safely, efficiently and economically. Kishore and Dewangan (2010) have examined and compared various methods for calculating the operating cost of dragline operations based on case studies.

Until recently, dragline monitoring systems have not had the capability for obtaining geometry data of the surrounding pit. In order to visualise the operational environment including the dig and dump locations, a digital terrain mapping (DTM) system has now been developed and has been embedded into the current, dragline monitoring-system. Roberts (2002) introduced this advanced, dragline-automation feature. The system is based on a laser scanner that utilises the rotation of the dragline to collect 3D data of the surrounding area. A nodding mechanism connected to the laser scanner enlarges the scanning plane, whilst a GPS unit has been installed to obtain accurate, real-world coordinates for the mapping. Despite the system’s hardware configuration, which was described in his earlier study, Roberts and other colleagues have also conducted their DTM data analysis based on the construction of mapping data (Roberts et al. 2003). This DTM system now has a significance usage in routine, mining operations to enable the better visualisation of the dragline’s working environment, which is ultimately beneficial for the productivity enhancement of the machine.

The contribution of a sequence optimisation for the dragline would be a very important step in its automation; this has thus been a popular topic in current industrial, mining research. Many researchers have examined and have developed systems for automating draglines for
the purpose of reducing the operational reliability of the operators. Several successful steps in dragline automation have been implemented with:

- The inclusion of the coordination of computer control in the excavation cycle
- The resetting of the bucket position at the end of the cycle
- An effective damping of the swing at the dump and dig sites
- An estimation of the bucket’s weight and with bucket recovery as discussed by Winstanley, Corke and Roberts (1999)

It was also noted, however, that an optimal trajectory and productivity study would be required for the development of automated swing cycles to quantify the potential benefits for the mining industry. Winstanley et al. (2007) have also described the significant stages of dragline automation, which have taken place over the last decade. The automation of the dragline’s swing-to-dump, excavation cycle has been achieved by the utilisation of the dragline’s swing-assist (DSA) system and via a provision of a facility providing an awareness of the machine’s surroundings via digital-terrain mapping (DTM) technology. Yet despite the application of automation technology in the excavation cycle, the dragline’s repositioning still, however, completely relies on the operator’s manual control. In fact, an automation of the process for repositioning of the dragline would be essential to achieve full autonomy.

### 1.2 The rationale for this research

The existing monitoring systems for draglines are useful tools for collecting key information that is related to their operation. This data will allow further development and analysis of dragline’s benchmark KPIs.

As dragline autonomy has been investigated for nearly a decade and, as dragline repositioning has not been covered in existing systems such as by Dragline Swing Assist (DSA) and by Digital Terrain Mapping (DTM), this thesis provides an opportunity for investigating the possibility for development of the optimisation of a dragline’s repositioning with the goal of enhancing its productivity.
The benefits of developing an algorithm for the optimisation of positioning of the dragline and of providing a more precise, decision-making capability to dragline operators on how they can improve the digging sequences may allow:

- An enhanced utilisation of the dragline and increased productivity, which would result from making the operators aware of the consequences of non-optimal sequences (the predictive algorithm, for example, might suggest an early dragline-repositioning so as to avoid more hoist-limited cycles).
- A reduction in energy consumption: Reducing the severity of hoist-limited cycles has the potential for reducing the energy consumption of the dragline by reducing total-cycles times.
- An extended, asset life: Fewer hoist-limited cycles have the potential to reduce boom and gearbox stresses and to enhance the life of the dragline’s components.
- A step forward to dragline automation: Autonomy of the repositioning process is capable of implementation with the existing, swing automation and the surrounding, supervision systems in order to establish an overall, dragline automation-system.

1.3 The aims and objectives of this research

The aims of this research are to develop:

- A back-analysis application of advanced, dragline performance-indices for the operational process
- A search-heuristic, optimisation-model for generating favourable, dragline walking-sequences for the draglines throughout the operational life of an entire, master mine-plan

Such an algorithm will permit an automatic process for the dragline’s repositioning by using a combination of dig and swing KPIs to provide operators with adequate advice on how to improve the dragline’s dig-sequencing. It will be based on a rolling-horizon plan.

In order to accomplish these aims, the following objectives have been adopted for this study:
1. To develop/utilise a suitable mathematical model(s) for classifying the dependencies of the operating cycles of the dragline.

2. To conduct benchmark analysis to acquire basic productivity-data, which has been specifically collected for the dragline, in order to develop the basis and constraints for an automation of the dragline’s walk-sequencing over any given excavation block.

3. To allow the dragline operators to be automatically informed of when to reposition the dragline in order to minimise the dig-cycle times and the short-term costs for the extraction of a given block.

4. To provide a suggested and optimised, dragline walking-sequence for repositioning the dragline within an excavation block.

1.4 The scope of this research

Due to the complexity of the algorithm’s development procedures, the scope of this project will be restricted to a specific dig-mode, side-casting mining-process with zero rehandling in a strip-mining operation, which uses conventional draglines rather than UDD machines. The typical swing-to-dump cycling operation will be expected for the purposes of analysis in this thesis, while breakdown and deadheading are not considered into the analysis. Also, only "steady-state" pit conditions are considered, i.e., no 3D problems - corners, ramps, faults, endwalls etc.

1.5 The research questions

The specific research questions for this thesis are:

- What are the motives for dragline operators to reposition draglines during block excavation and is it possible to automatically classify these on the basis of monitored data?

- Can a back-analysis algorithm be developed to optimise repositioning decisions so as to minimise overall swing and positioning costs?

1.6 Outline of the thesis
Chapter 1: Introduction. This chapter outlines previous research in relation to the optimisation of the dig sequences of draglines on open-cut coal-fields. It also provides a rationale, outlines the aims and objectives of the thesis, lists the research questions and defines the scope of the present study.

Chapter 2: Literature review. This chapter provides a literature review that is pertinent to the research questions as defined in this chapter. This chapter:

- discusses the major mining processes, which are related to the operation of a conventional dragline
- considers optimal walking-sequences for draglines
- considers the establishment of bench marks and performance indicators for the walking-sequences for draglines
- considers the coincident limit theorem

It then reviews the literature relating to the optimising of the performance of draglines including sequence optimisation, the genetic algorithm and goal programming.

Chapter 3: Methodology. This chapter describes the methodology that was used in this study including: the application of the coincident-curve algorithm and cost function, the data capture and the data filter and how the dig-blocks were determined. It also describes the thesis resources, the relative position of the dragline to the blocks and outlines the goal programming and the genetic algorithm.

Chapter 4: The dragline benchmarks. This chapter describes:

- the start-of-block and swing-classification approach (including the detection methods, the equivalent swing-angle signatures and the equivalent swing-angles, and the swing-performance benchmarks)
- the dragline’s cost-function (including the operator’s repositioning motives, the dig-reach overlap and the dig-matrix, and an analysis and classification of the repositioning motives)
- an approach-based classification of the repositioning of the dragline

Chapter 5: The genetic algorithm. This chapter introduces and defines the genetic algorithm, defines the constraints (for dig, swing and the excavation-block geometry constraints) and considers the genetic algorithm as a method for the optimisation of
the dragline. This includes a description of the overall approach, the population of the algorithm and the implementation of the algorithm. It describes how over-digging is detected and also presents the results of the validation process.

Chapter 6: Results and discussion: The results of this study are graphically presented and are then discussed in conjunction with the results validating the genetic algorithm.

Chapter 7: Conclusions: This chapter presents the overall conclusions of this thesis and re-evaluates the research questions. It also considers the limitations to the present study and provides recommendations for further research.
Chapter 2 Literature review

2.1 Chapter introduction

The dragline is a heavy, cyclic machine that moves material one from one position to another. The conventional dragline operation’s role in an open cut strip coal mine is to uncover the resource by removing waste from the coal seam surface. The dragline’s mining system is a relatively simple, versatile, low-cost, mining method. A single dragline has the capability of operating over a wide range of overburden depths with different material characteristic (Humphrey 1990).

2.2 The dragline and the related mining processes

The dragline cycle begins with the bucket being lowered into the pit and positioned to penetrate the bank. The bucket is filled by dragging it into the digging face. Although the buckets are designed to allow the teeth to have a good angle of attack in the relaxed position, sensitive handling of the hoist tension at this time can improve the penetration rate and can reduce bucket fill time. Once filled, hoisting and drag pay-out commences almost simultaneously, and this is followed by swinging as the bucket clears the trench. As the bucket swings and climbs, proper tension between the hoist and drag holds the bucket in the carry position. As the dumping point is approached, the swing control is reversed (plugged) and the drag allowed to pay out until the bucket is unbalanced and the load is dumped. Due to the swing inertia of the machine, the direction of swing will not change for several seconds after the controls are reversed, thus giving the bucket time to dump without delay. During the return swing, the hoist is paid out and the drag is reeved in so as to begin the positioning process as the bucket settles into position. The proficiency with which these five functions are carried out thus contributes significantly to the productivity of the machine (Sargent 1990).

2.2.1 The dragline and its repositioning operation

The operational process of moving a dragline through a number of positions to excavate a block in a generic block-to-spoil-type of mining operation is often referred to as sequencing (see Figure 2.1). The process by which the correct sequencing for an excavation block is
identified is generally via operator judgement. By identifying and quantifying the operational constraints and the motivations for individual movements in the sequencing process, it may be possible to assist the operators by providing an automatically-generated, optimal walk-sequence in each excavation block in terms of performance-indicators, which could then motivate them to move the dragline from one position to the next position in the sequence. The operators may also be assisted in identifying if the dragline is in a non-ideal location if they can be provided with information that the dragline is operating beyond the point of its most-efficient capability. The benefits for achieving this would be a greater consistency in, and a better compliance with, the most-efficient excavation-sequence and this will thus result in faster, coal-recovery rates.

![Figure 2.1 A sequencing diagram for a dragline](image)

The dragline time usage summary report (Wesfarmers 2015) suggests that approximately 9% of utilised time is spent on positioning, where utilised time is comprised only of cycling, positioning and unproductive cycling. Therefore, if 10% reduction in repositioning hours can be achieved, then the production can increase by 1%. It also shows that dragline positioning takes up the second largest percentage of the operation hours, following that of the productive cycling.

Dragline repositioning thus represents a significant component in a more, efficient utilisation of the machine and results, therefore, in faster coal-recovery rates. For the purposes of this thesis, positioning refers to either:
• The small, repositioning movements within the sequence of the digging out of a single excavation-block.

or

• The larger, repositioning movement when the dragline is moved from the end of one excavation block to the beginning of the next.

Other dragline positioning-activities are required during the dragline’s operations but these have less bearing on the efficient excavation of a block and will not be considered here.

Examples include:

• The ‘deadheading’ movement from one pit/strip to another pit/strip

• The positioning of the dragline for maintenance activities

• The positioning the dragline for safety-related reasons, such as at the end of a shift or for blasting exclusion-zone requirements

Repositioning within the excavation block is a required practice, which allows the dragline to both effectively reach the material that is to be dug and the spoil location. There are a number of motivations that drive the requirement for repositioning within an excavation block and which can be any combination of the following:

• The geometry of the block to be excavated

• The operating constraints of the dragline

• The observance of safe operating-practices

• The requirements for clean-up work in and around the digging or spoil area (this is generally performed by bull-dozers)

Irrespective of the causes or motivations for repositioning, there will always be a time interval that is associated with it. Several repositioning movements will be performed for any given sequence; these result in an increase in the time that is needed for completing the dig-excavation. The duration of the recovery time will thus also increase with an inefficient
movement, and this will consequently decrease the dragline’s overall productivity (Papachristou et al. 2010).

2.3 The performance indicators for draglines

Lumley and Haneman (1994) analysed the performance data from the Tritronics monitoring-system, which had been installed on sixteen Australian draglines. These authors considered a number of key process-variables including hoist-dependent swings. Those variables led to processing of the critical parameters for dragline-performance in order to evaluate productivity-enhancement for the different dig-sequences. A high percentage of hoist-limited cycles were found to be related to one or more of the following (Lumley & Haneman 1994):

- The pit and/or block geometry: The depth of overburden and the restrictions on spoiling (sometimes caused by a proximity to ramps), and geology can influence the percentage of hoist-limited cycles.

- The dragline’s chosen digging-method: The method chosen to uncover the coal can influence the incidence of hoist-limited cycles (for example, the ratio of chopping/digging, stand-offs, proximity to spoil etc).

- Its swing and/or hoist, motor capacity: A high percentage of hoist-limited cycles may prompt an evaluation of a business case for motor upgrades.

- Bucket-rigging geometry: Incorrect geometry can slow the swing-to-dump process by requiring tight trajectories close to the boom in order to maintain the bucket’s carry angles.

- The operator’s training: Operators may be positioning draglines too close to spoil piles or leaving hoisting operations until it is too late into the swing.

While the dragline’s digging-method and the operator’s training is highly subjective, these authors found that an investigation of block geometry and motor capacity would be very useful in reducing hoisted-cycle dependency.
With a substantial amount of dragline-monitoring data processing, the cycle times and dependencies are considered to be the significant operation-indicators. Erden and Duzgun (2005) also analysed performance data from two draglines that were operating in a Turkish mine and suggested cycle-time improvements. The majority of cycles, which were analysed, were found to be swing-dependent but the authors discovered, however, that the cycles became hoist-dependent for deep, narrow key-cuts. The cycles also had a high probability of being drag payout-dependent for swing-angles, which were smaller than 50 degrees.

Morey (1990) has suggested that dragline productivity in layer cutting will increase with a corresponding decrease in the operating costs. This can be achieved by decreasing the average swing-angle as the dragline progressively proceeds to the spoil pile. Morey also noted that small draglines are swing-critical when the panel widths are less than the required width for practical, coal operations and when cycle times increase sharply, whereas larger draglines become swing-critical when the panel width exceeds 50m. The required walking time per panel is shortened as the dig-out length increases. Repositioning in the dig-out will also affect cycle times; so repositioning times can be estimated by discounting the walking speed of the dragline. The discount factor is approximately 15 to 20%.

Scott and Thornton (2000) also observed and analysed the relationships between the dig constraints, which decide the rules of the dragline’s digging operation. These are:

- The fill time increases as the drag length is increased (see Figure 2.2)
- The drag length increases as either the start of fill-reach or the start of fill-height increases (see Figure 2.2)
- The optimal region for the dig time exists with a certain range of digging-radius and depth (see Figure 2.3)

The contour plot that revealed the relationship between the digging depth, the reach and the dig-time was next re-constructed with the actual performance data. With the utilisation of regression analysis, those interdependencies between the dig’s KPIs were then represented by a mathematical function, whereby the constraint’s deviation was then formulated by the minimum and maximum values.
Figure 2.2 Relationships between fill-time and drag-length (left) and between drag-length and start-of-fill (right)

(Scott & Thornton 2000, p.58-59)

Figure 2.3 The relationship between digging-depths, reach and dig-time (colour code unit is second)

(Thornton & Whiten 2003, p.6)

Komljenovic et al. (2010) proposed a novel approach for defining a performance indicator for a dragline operator. Their approach considers the relationship between the dragline’s production and its energy consumption. It uses confidence intervals in a Gaussian normal distribution of the ratio of hourly dragline production and hourly energy consumption in
order to classify the operator’s performance. This study implied that the operator has a large impact on the dragline’s performance and that this is an unpredictable and subjective factor with regards to the optimisation of the operation. In order to achieve further optimisation of the dragline’s operation, it is thus necessary to develop semi-automation systems for the dragline in order to minimise or, even, to avoid operator effects. This might include the use of the Dragline Swing Assist to automate the swing operation and the Digital Terrain Mapping to automate the surrounding supervision.

2.4 The coincident-limit theorem and the swing-cost model

Humphrey (1990) has further suggested a spoil strategy, which was called a ‘coincidence limit’, to optimise the swinging operation. A ‘coincident point’ is a point in space that is defined by the position of a loaded dragline-bucket, where the swing and hoist motors work at full capacity for an equivalent amount of time.

An algorithm that uses a simple, graphical approach has been developed to classify dragline cycle dependences (Knight et al. 2013). This is based on coincident limits as defined by the locus of points where the swing and hoist motors work at full capacity for equivalent amounts of time. It is capable of distinguishing three cycle-dependencies for swing, hoist and drag-payout limited cycles.

The coincident-limit algorithm was applied to the data from 200 000 cycles on a dragline at a mine in Queensland’s Bowen Basin. Seventy per cent of these cycles were found to be swing-limited, 27% of the cycles were found to be hoist-limited and the remaining 3% were found to be drag-payout limited.

The development of coincident-limit graphs facilitates the possibility of measuring dragline-work as BCMs multiplied by the equivalent swing-angles. This could be applied to benchmark dragline performances across different operations where differing pit and block geometries can influence the proportion of hoist-limited cycles.

There is also the potential to apply the coincident-limit algorithm to compare dragline swing-performances against historical performances in similar circumstances, and to compare a
Kline (1988) has proposed a cost function per horizontal, bucket-foot of movement to recommend the dragline’s repositioning. This study suggested that it would be better to leave the material for the next pass with a longer, swing distance if there was a minimum, swing angle that was too small. This cost function associated elevated costs with small, swing angles in the range of 0 to 40 degrees, and declining costs between 60 and 160 degrees. Dragline repositioning was recommended if the expected cost of remaining digging at a certain position exceeded the delay and dig costs, which were related to repositioning. This algorithm implied the association between the swing and the corresponding operation cost; it didn’t, however, consider hoist-limited cycles. Compounding Kline’s idea to this author’s ‘Coincidence Curve’ algorithm will provide an insight into a new cost-model, which includes both swing and hoist-limited cycles.

2.5 Optimising the performance of the dragline

2.5.1 Sequence optimisation

Operation optimisation has become an interesting aspect of dragline automation, which has led to a further investigation of a dragline’s walking sequence. Scott and Thornton (2000) suggested that dragline position determines the dragline’s excavation performance and dig sequence, that is, where it can dig, where it can dump the spoil and the swing distance. The location where the dragline is to be positioned and the reasons for repositioning are necessary to optimise the dragline’s walking sequence. These authors also described the relationships between the dragline KPIs for evaluating the operation’s performance.

Sier and Whiten (1993) have demonstrated that the minimised, cumulative swing-time could be achieved by removing the overburden in an optimal sequence. These authors attempted to address the problem via the application of a mathematical model with specific decision-parameters and an objective function, and used several methods such as an optimal, control formulation, a dynamic-programming approach and non-linear programming to solve the problem. Their study described a model for a dragline’s dig-sequence, but it failed to consider a detailed plan for the dragline’s repositioning.
2.5.2 The genetic algorithm

A multi-objective, genetic algorithm (MOGA) has also been applied to an innovative mine production’s scheduling scheme for ore, grade-control planning-tasks. This involved a scheduling exercise for the production-scheduling operations (Samanta et al. 2013). The underlying motive for the use of a multi-objective genetic algorithm was to develop pareto optimal-solutions in order to meet the targeted, grade-specification goal with multiple grade-attributes. New designs of concepts such as mutation operation and the convergence criteria of the algorithm were introduced to meet the real, working situation (see Figure 2.4).

![Diagram of MOGA for production schedule generation](image)

**Figure 2.4** The conceptual model of MOGA for the generation of an optimal production schedule

(Samanta et al. 2013, p.69)
Thornton and Whiten (2003) introduced the genetic algorithm to progressively improve the dig-sequences of draglines, which had been described by a series of control values. This genetic algorithm generated feasible and an improved new sequence based on the cycle-time constraint. These authors found that it was feasible to define the representation of the actual working-situation by inserting intermediate surfaces between the initial and the final profiles to generate random-walk sequences. A new design for the crossover and mutation operators was suggested in that study, in order to insert new intermediate profiles and to generate dig sequences to fill the gap after sequence section-swapping with unchanged beginning and end subparts, and to randomly select a dig sequence and an intermediate profile for applying these changes, respectively. This study provided an insight into the feasible application of this genetic algorithm to the dragline’s digging, swinging and repositioning operations. Apart from the cycle-time, however, hoist-limited swinging is one of the main constraints that affect the dragline’s dig-sequence and this was ignored in this study. The assumptions of the algorithm were also based on a fixed-horizon plan, which induced a lack of robustness.

2.5.3 The goal programming

Knights and Li (2006) applied a goal-programming technique to determine a weekly shovel-sequencing in the production schedule. The constraints on the objective function included the mining cost, the processing cost, the shovel’s productive capacity and the block accessibility. A similar methodology can also be applied to a dragline’s walking-sequence optimisation for both of them are walking machines with cycling operations.

2.5.4 The relevant software

The majority of the data analysis and algorithm development can be implemented in MATLAB, which is a multi-paradigm numerical computing environment. Matlab has the ability to access data from the files with popular file formats, such as Microsoft Excel, and databases. The MATLAB language also supports vector and matrix operations, which are essential for solving engineering problems and for enabling fast development as well as for swift execution (MathWorks 2015 (a)).

MATLAB also provides a range of toolboxes such as, for example, the Optimization Toolbox for solving minimisation or maximisation problems with defined constraints the Signal
2.6 Chapter summary

The process of dragline repositioning can be a major cause of the loss of productive dig-hours. As repositioning is a required activity for the excavation of a block, a trade-off exists between the decision to remain digging at a particular location and the decision to reposition in order to achieve more favourable dig-conditions, swing angles, or other operational considerations. The dragline crew currently require considerable skills and experience to position the dragline for maximum productivity without compromising the site-requirements of the dig-plan or of safe, operating practices. The optimisation of the dragline-repositioning would be beneficial to enhance productivity.

The performance of the dragline’s operation can be evaluated by utilising selected dragline-KPIs. Cycle-time, cycle-dependency, digging-block dimensions and dig, swing, as well as dump KPIs would be helpful in indicating the overall performance of the dragline in a given excavation block. These performance indicators are the key variables for optimising the repositioning of the dragline. Amongst these, cycle-dependency has a strong association with swing operational-cost, which is another important parameter (apart from cycle and positioning time), to minimise the operational costs and to optimise the repositioning of the dragline. A cost calculation model is thus required to effectively compute the swing-operational costs with the consideration of cycle-dependency in the dragline’s digging-sequences.

The automatic generation of an optimal, walking sequence for a dragline, which has a swing and dig-control objective, is always challenging. The exact, machine tub-positions at the time of digging are initially unknown; a schedule thus needs to be constructed to generate feasible sequences within a particular excavation block. As a result, the expected productivity from a particular excavation sequence may not be fulfilled. There might also be several thousands of possible excavation sequences for the blocks from which the best solution has to be obtained. An optimisation algorithm thus needs to be devised for this purpose. The required algorithm needs to be designed in such a way that it is able to handle multiple and targeted constraints with a stipulated goal. The genetic algorithm has the advantage of being able to solve
problems without clear solutions and including problems with multiple solutions and objectives and the capability of being able to avoid being trapped in local optimal solutions (Samanta et al. 2013).
Chapter 3 Methodology

3.1 Chapter introduction

This research consisted of four modules (see Figure 3.1); these were: data analysis, modelling, algorithms and implementation with the ultimate goal of advising the dragline’s operator on the optimal repositioning of the dragline.

Figure 3.1 The thesis design

An analysis of the captured data from the monitoring system was undertaken to define the dragline’s dig and swing constraints in the goal programming to obtain a fitness function for the purpose of achieving a further optimisation in the genetic algorithm. Back analysis and program coding was undertaken at the stage of algorithm implementation.

3.2 Thesis resources

Wesfarmers Resources has made the performance-monitoring data for a suitable dragline available for this study, for the purposes of developing and of testing the classification’s algorithms. Wesfarmers also made the Pegasys monitoring system available on one dragline
in order to implement and to field test the algorithm. The cost histories over a representative one-year period were also made available for capital analysis by Wesfarmers.

Mineware Pty Ltd has already developed the necessary, software interfaces for displaying context-sensitive performance-indicators to dragline operators and monitoring-system software for third-level operation-monitoring. This was a critical tool for collecting the real-time data of dragline-performance-indicators for further analysis and processing. This system was available for a suitable dragline so as to generate data to meet this research’s source requirements.

### 3.3 The coincidence-curve algorithm and the cost function

A coincidence-curve algorithm had been previously developed by this author to determine the hoist, swing and drag-limited cycles (Knights et al. 2013). This coincidence-curve enabled the visualisation of a trajectory or curve that was defined by the loci of coincident points; these were points in space that defined the position of the loaded dragline-bucket where the swing and hoist-motors worked at full capacity for an equivalent amount of time (Humphrey 1990). The potential, vertical lift was small for correspondingly, small swing-angles but larger lifts were possible for larger swing-angles until the full, dump-height capability of the dragline had been achieved. The use of a coordinate system, which was defined by the dragline’s swing-angle on the x-axis and by the vertical lift-height on the y-axis, enabled the visualisation of a trajectory or curve, which was defined by the loci of such coincident points. This curve was designated as the “coincident-limit” (see Figure 3.2). A boundary of tolerance (error) was also defined in the paper to suggest that if a dump point of a cycle falls close enough to the coincidence curve, the cycle will still be classified as a balanced cycle (Knights et al. 2013). It was also possible to define coincident-limits between the swing and the drag, and between the hoist and the drag movements. The vertical and horizontal lines near the origin defined these limits, respectively.

If comparatively little hoisting is required within a cycle, or if hoisting is slowed for any reason, then the bucket’s dump position will fall below the swing/hoist coincident-limit. The lower half of the graph (below the swing/hoist limit in figure 3.2) thus denotes swing-limited cycles.
Conversely, if more hoisting time is required, thus necessitating a slowing of the swing motors, then the resulting cycle will be hoist-limited. The upper half of the graph (above the swing/hoist coincident-limit in Figure 3.2) represents hoist-limited cycles. If the bucket’s dump-position falls within the rectangle that is defined by the swing/dump and hoist/dump limits, then the resultant cycles are drag-payout limited. This could occur, for example, as part of the preparation work for the bench.

The equivalent swing-angle was thus defined from the coincidence-limit algorithm as the computational swing-angle where the full, dump-height capability of the dragline is achieved in hoist-limited cycles. It was thus the angle that could have been swung by the dragline given the hoist-height that was required. It was an important indicator of the dragline’s operational performance, and this will be further analysed in this thesis since it is a measure of how effectively the full electro-mechanical capability of the dragline is being utilised on a cycle-by-cycle basis.

Figure 3.2 The locus of coincident-points that make up a coincident-limit diagram

A dig-sequence algorithm based on cost-minimisation was previously established by Kline (1988). This cost function implied a relationship between the cost per bucket-foot and each
swing-angle. The repositioning of the dragline will be recommended to the operators if the expected digging-cost at a particular position exceeds the corresponding cost of the function.

The facility of this dependency classification of the cycles according to the coincidence-curve algorithm can be employed to improve Kline’s repositioning algorithm. To consider the cost, which is associated with the hoist-limited cycles, a new cost-model of equivalent swing-angles will be investigated via the analysis of collected, operating-cost histories over a one-year period for a dragline at the Wesfarmers Curragh mine-site in Central Queensland (see Figure 3.3).

Figure 3.3 The dragline at Curragh mine-site (Marion 8750)

The coincidence-curve algorithm will be used as the rule for defining the dragline’s swing-constraints in the goal programming.

3.4 Data capture and the data filter

A dragline’s excavation-sequence consists of: where the dragline stands, where it digs from and dumps to, and when and where it moves. A number of key process-variables were thus considered for the dragline during the data-analysis stage of the cycle. Dragline positioning-steps were required to discriminate the excavation blocks where: the GPS data located where the dragline stood, the cycle’s swing angles, the vertical hoist heights and the payloads were
related to the coincidence-curve algorithm to classify the cycle’s limit. The fill and dump locations were the keys for analysing the digging conditions at a particular position. This performance data was captured via the Pegasys monitoring systems of Mineware Pty Ltd, which provided an immediate access to real time and to historical, operational-data.

The following KPIs were required for the calculation of the equivalent swing-angles by the coincidence-limit algorithm. This necessitated:

- The swing angles
- The vertical hoist-heights
- The payload

The required data for the particular dragline’s walk was collected via the Mineware-Pegasys, dragline monitoring-system during June 2012.

Unusual operating cycles, which can be detected according to the cycle time, were filtered out to guarantee a consistency in the cycle-data. The cycle-outliers were defined as those cycles with extreme cycle-times.

Table 3.1 Lists the filter scheme with upper and lower, cycle-time thresholds.

<table>
<thead>
<tr>
<th>Cycle Outliers</th>
<th>Cycle Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short Cycles</td>
<td>&lt; 30s</td>
</tr>
<tr>
<td>Long Cycles</td>
<td>&gt; 120s</td>
</tr>
</tbody>
</table>

Any cycles that were shorter than 30 seconds or longer than 120 seconds were thus filtered out as outliers.

Since the central idea behind this thesis was to analyse and to improve the swing-operation, this research was trying to reduce the hoist-limited cycles in order to improve the swinging
performance of the dragline. This data thus focused on the swing-limited and on the hoist-limited cycles whilst the drag-limited cycles were thus beyond this project’s scope and were regarded as outliers to be filtered out.

3.5 Determining the dig-blocks

Repositioning is a major component of the dragline’s operation. There is a certain pattern in the dragline’s walking path and positioning in each block, which reflects the operational performance of the machine.

The strip on which the dragline works is divided into blocks. One excavation or dig-block is that area where the dragline is digging. The dragline will follow a set sequence on most blocks in order to remove the overburden. In any set sequence, the dragline will be relocated to several new positions within the block for the purpose of obtaining a more-favourable digging-operation.

To start a new dig block, the dragline conducts movements across the entire block to where it is currently digging to the edge of next block. The large number of activity steps that the dragline undertakes is thus a potential indicator of an initiation of a start-of-block activity. Variations in the fill-depths exist at various positions within an excavation block according to the volume of the material being dug. A shallow fill-depth also strongly infers the initiation of a start-of-block activity.

3.6 The relative position of the dragline to the blocks

Referring the dragline locations in each block to the corresponding first-tub position facilitated the data collection and the analysis. The first tub-position of the dragline in an excavation was the start-of-block position, which then incremented the position number as the dragline progressed.
The following Figure 3.4 provides an example of the method employed for displaying the dragline positions within a digging-block. The tub-positions, which comprised numbers 3 to 8, represented one block - the first block position was 3, the second one was 4 and so on, until the last one, which was 8. The next block started from number 9.

![Figure 3.4 Dig-block 1 with its related tub-position sequence](image)

A new coordinate system was thus built; the first block position became the start (origin) point of that box, where \((x,y) = (0,0)\). The coordinates of the rest were then defined as being relative to the original points.

### 3.7 The goal programming

An optimisation programme was developed to advise the dragline operators on when and where to reposition the dragline in order to minimise the short-term costs and cycle-times for the extraction of a block. Goal programming was able to handle the multiple, conflicting objective-measures, which were associated with relative, dragline-cycle data-analysis. Three types of constraints were classified as dig, swing and bench constraints and these were related to unwanted deviations from this set of target values, which were minimised in the objective function. The definition of the objective function thus reflected the weights of each constraint and evaluated the fitness of each, possible repositioning in the following, genetic algorithm. The diagram of the goal-programming procedure is displayed in the following Figure 3.5.

The ultimate goal of this stage was to determine an objective function in terms of the dig and swing constraints in conjunction with the block-geometry limits as a fitness indicator. This then enabled the evaluation of the fitness of the individual elements in the genetic algorithm.

The cost function took the number of hoist and swing-limited cycles, swing times and position distances into consideration. It was a linear function with weighting factors, which
was able to distinguish the priority level of each constraint. The fitness results were then able to be interpreted as the normalised swing and positioning costs of each sequence.

The swing cost was calculated by the following equation (3.1).

\[
C_{swing} = \sum (BCM \times \theta_{eq\_swing} \times C_{BCM/degree})
\]

(3.1)

Where:

\(\theta_{eq\_swing}\) was the calculated, equivalent swing-angle (see section 3.3)

BCM represented the cycle BCM

\(C_{BCM/degree}\) was the cost function (see section 4.3) (per BCM per degree)
Since the positioning cost was linear to the distance of the dragline’s relocating path, this was given as $C_{\text{position}} \in \alpha L_{\text{path}}$ and the machine’s positioning distance in each excavation block was computed as the positioning cost of a particular sequence.

In order to equalise the effectiveness of both costs, a normalisation was applied to achieve the same scale of swing and positioning costs. This was achieved by substituting $C_{\text{swing}}$ and $C_{\text{position}}$ in the normalisation formula in equation (3.2) to obtain the normalised values of the cost where:

$$X_{\text{norm}} = f(x) = \frac{\sum |x - \text{mean}(x)|}{\text{Std.}(x)}$$

(3.2)

The total cost was, thus, the sum of the normalised swing and positioning cost factors in equation (3.3) where:

$$C = f(C_{\text{swing}}) + \alpha f(C_{\text{position}})$$

(3.3)

Where:

$\alpha$ was a weighted factor for the position cost.

3.8 The genetic algorithm

A progressive learning-algorithm was applied to optimise the dragline’s dig-sequences in order to generate a complete and favourable excavation-sequence for a production-scale dragline. The genetic algorithm, where a better solution was derived by considering a series of constraints, was able to progressively improve the dig sequence. A new sequence was created during the iteration by a mutation and crossover amongst the population of dig sequences. Sequences, which had lower fitness values when compared to those in the rest of the population, were removed through iterations. This process was repeated until an optimal solution had been derived. A diagram of the general genetic algorithm can be seen in Figure 3.6.
In this research, a genetic representation of the solution domain was the sequences of the excavation positions of the dragline, which was generated randomly in terms of the corresponding dig and dump locations, whilst the fitness function was the objective function that was obtained from the goal programming (see Equation 3.3) after considering the dig, swing and bench constraints (see section 5.2). In order to follow the general rule in the genetic algorithm that higher fitness score indicates more favourable individual, the fitness function in the algorithm was the inverse of the normalised cost function in equation 3.3 (see equation 3.4).

\[ F = \frac{\beta}{C} \]  

(3.4)

Where:

- \( F \) is the fitness score of an individual
- \( \beta \) is a scale factor
- \( C \) is the cost function in equation 3.3

Random changes in the walking sequences within a feasible, reality range and with the swapping of walking-sequence sections (which had an identical start and end), provided the crossover and mutation processes to generate new sequences. A diversity and proximity value for each individual of a sub-population at a certain stage was computed to indicate the diversity and the proximity level of the new generation. The probability of an individual’s selection was then modelled using the roulette-wheel selection, which was based on each individual’s relative fitness. The algorithm was terminated by the defined maximum number of iterations, which was selected based on data analysis to indicate when the fitness score of each individual flattens and reaches its optimum.
The algorithm was then back-analysed via its application to the data, which had been collected over a representative, one-year period. The cost savings, which were apparent due to an optimised dig-sequence, were determined through the implementation of the algorithm.

(Corbilla 2010 p.1)
Chapter 4 The benchmarks for the dragline

4.1 Chapter introduction

Performance-monitoring data from the Mineware-Pegasys, dragline monitoring-system on an operating dragline at the Curragh mine-site in Central Queensland was collected for the period from February to June 2012. The activity log and the cycle log data were both captured and were processed to determine the dragline’s positioning and to analyse the corresponding patterns of the excavation blocks.

A repeated, triangular pattern (see Figure 4.1) was detected in the dragline’s walk-path, so the corresponding data set was extracted and analysed. Sixty-nine dragline positions, which were associated with nearly 10000 cycles, were categorised into twelve excavation-blocks.

Figure 4.1 shows the dragline’s UTM (universal transverse-mercator) tub positions; the x-axis recorded the eastings whilst the y-axis recorded the northing. The points of numbers on the graph represented the machine’s location during the digging. The numbers represented the dragline’s walking sequence, whilst each dig-block was classified in the shape of a triangle that is, for example, marked out in red. The step-threshold of these relocations was determined as fifteen steps.

The start-of-fill heights of the selected, twelve blocks are plotted in Figure 4.2. This graph illustrates a regular, fill-depth pattern where the fill-depth increases as the dragline carries out the process of removing the overburden; this contrasts to the average fill-height of less than ten metres at the initial position of each block.

Since the persistence of certain, dragline walk-patterns in the twelve dig-blocks implied a similarity of operations in the excavation blocks, a comparison of the performance data was also undertaken for the positions and the blocks to understand the motives behind each repositioning.
4.2 The start-of-block and swing classification approaches

4.2.1 The start-of-block detection methods

An analysis of the results in Figure 4.2 indicated that the blocks were generally fifteen to twenty-five metres in length. The length of a dragline-step varied from one make of dragline
to another. The step-size of a dragline was approximately one to two metres. The length of the block was governed by the depth of overburden of the coal and by the dragline’s reach. The movement of the dragline from one block to another was thus between fifteen and twenty-five steps, but this varied for different draglines.

The dragline’s positioning step could thus be considered to be a measurement of block division. It can be said, therefore, that the initialisation of a new dig-block followed fifteen to twenty-five step movements. Whilst the threshold for these positioning steps depended on different operational circumstances, this was, however, decided on the basis of the data from the dragline’s performance-monitoring system and the walking distance and was also calculated to verify the length of the activity-steps.

In order to increase the accuracy of the detection of the start-of-block points, the initial fill-depth was also delineated as another measurement of block division. Analysis of Figure 4.2 shows that the depth of the initial diggings was above ten metres, whilst the fill-depths at other positions exceeded ten metres and could thus be approximately up to forty-five metres.

This has led to the development of a threshold method for detecting the start position of a dig-block, which is shown below in table 4.1.

Table 4.1 The start-of-block detection method

<table>
<thead>
<tr>
<th>The start-of-block is detected if:</th>
</tr>
</thead>
<tbody>
<tr>
<td>• The activity steps are greater than 15</td>
</tr>
<tr>
<td>• The walking distance is greater than 15m</td>
</tr>
<tr>
<td>• The start/fill-height exceeds 10m</td>
</tr>
</tbody>
</table>

Figure 4.3 shows the classified start-of-blocks as red circles. The accuracy of the classification for this pit was 100%. This method was also applied to a second pit, which had been randomly selected (as shown in Figure 4.4), to validate this classification approach. It can thus be seen that the initial digging-positions were clearly detected.
The start-of-block detection algorithm thus had a high reliability and accuracy for the purposes of industrial implementation and it effectively led to optimal block-division.

Figure 4.3 The dragline’s walking-path with the identified start-of-blocks as red circles

Figure 4.4 The second dragline’s walking path with the identified start-of-blocks as red circles
4.2.2 The equivalent swing-angle signatures

The phase of swing starts when the bucket clears the ground and finishes when the mouth of the bucket inclines down at the dump location. Amongst all of the component activities in a dragline’s operational cycle, swinging takes up the bulk of the cycle-time; it is thus a significant element. The term ‘equivalent swing-angle’, which was derived from this author’s previous work on the Coincidence Limit Algorithm (Knight et al. 2013), was thus introduced here as a dragline performance-indicator for evaluating the swinging performance in each cycle.

The equivalent swing-angles were analysed on a positional basis for comparing the swing-operations between the positions and the blocks. The results are presented below using box-and-whisker plots to give a “swing signature” for each position in order to evaluate the swing-performance of the blocks. Useful insights into the repositioning motives of the operators were thus obtained from these swing-performance comparisons between the positions.

4.2.3 The equivalent swing-angles and the swing-performance benchmarks

Equivalent swing-angles were calculated for all digging positions from the twelve blocks for each operating-cycle during the study period. These were clustered into positions, which were relative to the start-of-blocks, and they were compared between the blocks. Swing-performance benchmarks were also generated for the dragline’s operation at the same relative locations in an excavation sequence. This data has been summarised in Figure 4.5 to Figure 4.9 using box-and-whisker comparison-plots.

In these plots, the x-axis represents the number of each dig-block and the y-axis represents the equivalent swing-angles. The number of cycles at a certain position in each block is displayed at the bottom of the graph, whilst the numbers at the top are an average of the equivalent swing-angles at the particular position. The positional plot on the right of the swing-signature shows the corresponding, dragline location in comparison to the swing benchmarks (see the red circles).
There are five number-summaries in the box-and-whisker plots. These are:

- The sample minimum - this is the lowest bar of each whisker as the smallest observation
- The lower quartile - the bottom of the box is the 25th percentile
- The median - the band near the middle of the box is the 50th percentile
- The upper quartile - this is the top of the box and is the 75th percentile
- The sample maximum - this is the top bar of each whisker as the largest observation

These plots show the differences between the equivalent, swing-angle populations without making any assumptions about the underlying, statistical distribution. The spacing between the different parts of the box helped to indicate the degree of dispersion and skewness in the data and to identify the outliers.

Figure 4.5 The swing-signatures at relative position 1
Figure 4.6 The swing signatures at relative position 2

Figure 4.7 The swing signatures at relative position 3
Figure 4.8 The swing signatures at relative position 4

Figure 4.9 The swing signatures at relative position 5

A certain range for the equivalent swing-angles at each dragline-location can be noticed from the graphs above; this increased as the machine repositioned. Outliers such as blocks 6 and 7 and swing variations in some blocks existed; these can affect the overall performance during this operational period.
The observation of operational differences, which were related to inconsistent equivalent, swing-angle signatures, was assisted by this swing-signature comparison and this facilitated the operational-performance feedback to the operators for the purpose of productivity-enhancement.

4.3 The dragline’s cost-function

4.3.1 Determining the swing’s control-limits

Draglines are the most expensive pieces of excavating equipment that are found at a mine site and it is important that they are operated safely, efficiently and economically. The ultimate goal of the dragline’s operation is to maximise the coal’s exposure rate whilst minimising its unit cost.

As swinging is an important component in the cycling operation, it was important that relationships should also be established between the swinging KPIs, which included the equivalent swing-angles, and the dragline’s operating-cost. A cost-model was developed for the dragline as a cost per BCM-degree function of the equivalent swing-angle and this thus defined a window of equivalent, swing-angles to minimise the operating cost and to optimise the swinging performance. This cost-function was then useful for further data analysis and implementation.

4.3.2 The operational costs of the dragline

The general operating costs of the dragline included: the supervision and labour, the salaries and wages, the labour burden, all of the expendable mining supplies, the operation of the major mining-equipment (including the maintenance parts, the electrical power, an allowance for the undistributed overheads of the mine offices such as office supplies, engineering supplies, general maintenance supplies, and local property taxes and insurances (Borquez & Thompson 1990) . The sources of the operational costs were categorised into summaries and these are shown in table 4.2. A label that is fixed or variable was then assigned to each cost-source item.
The variable cost is the cost that depends on the operating cycles and this varied according to the number of cycles and swing-angles whose unit was in dollars per production hour. The fixed cost was applied to the machine’s operations regardless of the actual operating-cycles.

The total variable-cost was the sum of each variable’s cost-source including: parts and consumables, GET, wire ropes and bucket teeth, and lubrication and power. The total fixed-cost was the total of such fixed-cost items such as maintenance labour, contract services, labour operators and others.

Table 4.2 The operational cost-elements of the dragline

<table>
<thead>
<tr>
<th>Cost source</th>
<th>Cost type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parts and consumables</td>
<td>Variable</td>
</tr>
<tr>
<td>Maintenance labour</td>
<td>Fixed</td>
</tr>
<tr>
<td>Contract services</td>
<td>Fixed</td>
</tr>
<tr>
<td>GET Bucket teeth</td>
<td>Variable</td>
</tr>
<tr>
<td>Wire ropes</td>
<td>Variable</td>
</tr>
<tr>
<td>Lubrication</td>
<td>Variable</td>
</tr>
<tr>
<td>Power</td>
<td>Variable</td>
</tr>
<tr>
<td>Labour Operator</td>
<td>Fixed</td>
</tr>
<tr>
<td>Others (overheads etc.)</td>
<td>Fixed</td>
</tr>
</tbody>
</table>

Other elements, which were involved in the cost calculations, were:

- The annual, total operating-hours
• The cycle per production-hour
• The effectiveness of utilisation
• The annual prime-production

4.3.3 The derivation of the equivalent swing-angles

The derivation of the equivalent swing-angles involved data from the swing-angles, from the vertical hoist-heights and from the payloads as captured in 2012 by Mineware-Pegasys’ dragline monitoring-system. This distribution is shown in the following Figure 4.10

![Equivalent Swing Angle Distribution](image)

Figure 4.10 The distribution of the equivalent swing-angles

As shown in Figure 4.10, the equivalent swing-angles formed a Gaussian distribution with the majority falling between 75 and 150 degrees.

Due to the effects of the numbers of the cycles and the swing-angles on the variable operational-costs, the following two parameters were investigated from the data collected between February and June 2012 to contribute to the development of the cost model. These parameters were:

• The number of cycles that had been completed by the dragline
• The frequency distribution of the equivalent swing-angles
The parameters of the cost function were:

- The total cost, the sum of the variable costs and the fixed cost or $cost_{total}$
- The variable cost or $cost_{var}$
- The fixed cost or $cost_{fixed}$
- Total number of cycles or $number_{cycle}$
- The cycles per production hour or $cycle_{hr}$
- The equivalent swing-angle or $angle_{eq}$
- The total BCM or $BCM_{total}$
- The BCM per cycle or $BCM_{cycle}$
- The annual total operating hours or $Hrs_{total}$
- The effective utilisation or $\eta$

The frequency distribution of the equivalent swing-angle is shown as a histogram, which depicts the number of cycles as a function of each equivalent swing angle where:

$$number_{cycle} = f(angle_{eq}) \quad (4.1)$$

and

$$number_{cycle} = Hrs_{total} \times cycle_{hr} \quad (4.2)$$

Assuming the variable cost was a linear function of the number of cycles with a coefficient or $coeff$, then:

$$cost_{var} = coeff \times number_{cycle} = coeff \times f(angle_{eq}) \quad (4.3)$$

$$= g(angle_{eq})$$
\[
coeff = \frac{\text{cost}_{\text{var}}}{\text{number}_{\text{cycle}}} = \frac{\text{cost}_{\text{var}}}{\text{Hrs}_{\text{total}} \times \eta \times \text{cycle}_{\text{hr}}}
\] (4.4)

The cost per BCM was also then calculated from the total cost and the total BCM for a certain period:

\[
\$/BCM = \frac{\text{cost}_{\text{total}}}{\text{BCM}_{\text{total}}}
\] (4.5)

\[
\$/BCM = \frac{\text{cost}_{\text{var}} + \text{cost}_{\text{fix}}}{\text{number}_{\text{cycle}} \times \text{BCM}_{\text{cycle}}}
\] (4.6)

Substituting equation (4.1) and equation (4.3) into equation (4.6) gave:

\[
\$/BCM = \frac{g(\text{angle}_{\text{eq}}) + \text{cost}_{\text{fixed}}}{f(\text{angle}_{\text{eq}}) \times \text{BCM}_{\text{cycle}}}
\] (4.7)

\[
\$/BCM = \frac{g(\text{angle}_{\text{eq}})}{f(\text{angle}_{\text{eq}})} \times \frac{1}{\text{BCM}_{\text{cycle}}} + \frac{\text{cost}_{\text{fixed}}}{\text{BCM}_{\text{cycle}}}
\] (4.8)

\[
\$/BCM = \frac{\text{coeff}}{\text{BCM}_{\text{cycle}}} + \frac{\text{cost}_{\text{fixed}}}{\text{BCM}_{\text{cycle}}} \times \frac{1}{f(\text{angle}_{\text{eq}})}
\] (4.9)

\[
\$/BCM = a + \frac{b}{f(\text{angle}_{\text{eq}})}
\] (4.10)

Where \(a\) and \(b\) were constants such that:

\[
a = \frac{\text{coeff}}{\text{BCM}_{\text{cycle}}}
\] (4.11)
\[ b = \frac{\text{cost}_{\text{fixed}}}{\text{BCM}_{\text{cycle}}} \]  \hspace{1cm} (4.12)

Thus,

\[ \$/\text{BCM}/\text{angle}_{eq} = \frac{a}{\text{angle}_{eq}} + \frac{b}{f(\text{angle}_{eq}) \times \text{angle}_{eq}} \]  \hspace{1cm} (4.13)

Figure 4.11 displays the result of the cost function for the equivalent swing-angle. In the cost-function plot with $$/\text{BCM}/\text{degree}$$ as the y-axis and the equivalent swing-angle as the x-axis, the cost per BCM per degree declined at small angles that were less than 60 degrees; The function flattened with a low unit cost between 60 and 160 degrees. The minimum point was reached at 120 degrees and this was followed by a slight climb in the curve. The big drop at the beginning is due to the filtered, drag-limited cycles.

Figure 4.11 The cost function of the equivalent swing-angle

4.3.4 The equivalent swing-angle run-charts

The optimum operational-range of the equivalent swing-angles was obtained from the above to be between 60 and 160 degrees. This swing cost-limit provided a measurement for the evaluation of the swinging-performance at each digging-position. Cycles beyond the swing cost-limits, which were either over-limited or under-limited, can then generate a warning to
provide a feedback to the operators to suggest that there is a need for the repositioning of the dragline.

Equivalent swing-angle run-charts assisted in visualising the swing-performance of the excavating positions after calculating and plotting the equivalent swing-angles of every cycle against the time sequence (see Figure 4.12 to Figure 4.23). The red-dashed lines represent the upper and lower swing-limits for minimising the operational costs. A comparison of these run-charts illustrates the variety of operational performances for each position in the excavation-blocks.

Figure 4.12 The equivalent swing-angle run-charts for block 1
Figure 4.13 The equivalent swing-angle run-charts for block 2

Figure 4.14 The equivalent swing-angle run-charts for block 3
Figure 4.15 The equivalent swing-angle run-charts for block 4

Figure 4.16 The equivalent swing-angle run-charts for block 5
Figure 4.17 The equivalent swing-angle run-charts for block 6
Figure 4.18 The equivalent swing-angle run-charts for block 7

Figure 4.19 The equivalent swing-angle run-charts for block 8
Figure 4.20 The equivalent swing-angle run-charts for block 9

Figure 4.21 The equivalent swing-angle run-charts for block 10
Figure 4.22 The equivalent swing-angle run-charts for block 11

Figure 4.23 The equivalent swing-angle run-charts for block 12
After the analysis of the equivalent swing-angle run-charts for all the 12 blocks (see Figure 4.12 to Figure 4.23), it was found that the majority of the swing-operations fell within the control limits for which the minimum cost had been calculated. Outliers appeared, however, at certain positions and more than 10% of the cycles were beyond the limits. These latter were an indicator of the performance-improvement, which is required at those particular digging-locations.

4.4 Classification of the repositioning of the dragline

The motives for the dragline’s repositioning were also investigated and classified according to the performance-data analysis. Mathematical methods were applied as tools to help to process the repositioning data and to develop the repositioning classification-algorithm.

4.4.1 The operator’s motives for repositioning the dragline

The operator’s motives behind each move had to be clearly discerned in order to better understand the dragline’s walking sequence; these were also determined by the location and by the operation of the machine.

There were several factors contributing to each move. These were:

- The lack of dig materials
- The lack of spoil room
- A non-optimal swing-angle (hoist- dependency)
- Stay
- Geotechnical concerns for the bench
- Drag ropes to kept clear of the bank crest

Geotechnical concerns for the bench depended upon the actual operational-situation and varied on different mine-sites. Excessive wear of the drag ropes can result from poor machine positioning relative to the bank crest. This is particularly prevalent when an operator begins the second cut from the dragline key cut position. This thesis only focused on an analysis of
the dig material, the spoil room and the swing-angle. It simply categorised any unclassified factors as ‘others’.

These repositioning motives thus provided the rules for defining the dig and swing constraints for the goal programming and for the development of the genetic algorithm, which is presented later in this thesis.

4.4.2 The dig-reach overlap and the dig-matrix

The immediate area where the dragline is working varies according to where the machine stands. Each tub-position corresponds to the particular dig-zone where the volume of the digging material is overlapped by the adjacent machine’s position. The amount of the overlap material reveals the extent of the material that is left in the previous digging-area and this thus affects any decision for repositioning.

The dig-location is regarded as the cross-section of the dig-reach and of the dig height. The overlap-area of removed material is where the digging-locations are shared corresponding to adjacent machine-tub positions. Unparalleled tub-locations along with the high-wall crest will result in an offset of the dig-reach between two sequential positions. This needed to be subtracted before any further calculations.

A constraint-matrix for the dig was also developed, see the example in table 4.3, which lists the percentages for the dig-location’s overlaps of the current and the next position in an excavation block. It also determined the amount of material that was left to be removed from the next excavating-position of the machine. By relating the percentage of this overlap to the volume of material that could be removed in the next position, the grid statistically assisted in the accuracy of the repositioning decisions.

Each row in this represents the number of current positions and each column represents the number of the next location to which the dragline was about to position. The percentage indicates the amount of overburden that was left between the current position and the next position.
Table 4.3 The dig-constraint matrix for block 1

<table>
<thead>
<tr>
<th>Percentage</th>
<th>Next Possible Positions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Current positions</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>6</td>
</tr>
</tbody>
</table>

The dig-constraint matrix was an effective measurement for revealing the amount of available digging-material that was remaining at the previous dig-section and, if the overlap percentage fell below a certain threshold, it was thus possible to classify the repositioning motives as being due to the lack of digging material.

4.4.3 The motives behind the repositioning-decisions

Dragline repositioning-motives were classified into four categories. These included: dig, spoil, swing and others. In each category, the utilisation of a recognised threshold determined the effects - through the data process, of the corresponding motives for the dragline’s repositioning. It is possible that more than one motive could have been categorised for each repositioning-activity due to the combination of dig, spoil and swing-activities in the machine’s operations.
4.4.4 A classification of the repositioning motives

The dig-motive is related to when the dragline relocates as a result of the lack of digging-material at the then current position. The dig-constraint matrix, which was developed above as shown in table 4.3, was an effective measurement for classifying the repositioning-motives for the dig. Since the matrix calculated the overlapping dig-material between two sequential positions, the determination of a percentage threshold was then useful in assisting in determining this motive. The matrix data-analysis indicates that, if the percentage of the digging-location’s overlap between adjacent positions was less than 10%, then the relative repositioning could then be regarded as being motivated by the dig operation.

The swing-phase is the next and main component in an operating cycle, when considering the required operation time. A non-optimised swing, which refers to a hoist-limited swing in a hoist-dependent cycle, has a large and negative impact on the dragline’s repositioning. The concept of hoist dependency in any particular cycle with a long-hoist, short-swing and pay-drag is that a slow swing-motion is required to permit hoisting. This imposes a large strain on the machine and slows down the entire process; it should thus be minimised. Repositioning must then be considered to seek a more-favourable swing-operation. Since hoist-limited cycles during swinging most likely occur in the latter stage of cycles recorded in any given dragline position, the swing motive for repositioning can be detected if more than half of the cycles in the last 20% of the cycling period at a certain tub-position are hoist-limited, where threshold was selected based on historical data analysis and experiments to give a most reasonable result.

The available spoil-room, which is required for dumping the waste material after the swing operation, varies during different operations. At any particular excavating-position, the waste material is more likely to be dumped at a designated spoil-area. The limitation of having a spoil-room at the end of each excavation-position leads, however, to machine repositioning. An important factor for detecting the change in the spoil-room is the dump-height. A sudden change in the dump-height data in the last 20% of cycles at a certain position thus implied that waste was being dumped into a new spoil room and that repositioning should thus be considered to ensure that the swing-to-dump angle was optimised.

Apart from the three main motives discussed above, others such as geotechnical motive will be categorised as “other motives” and will not be investigated in this thesis.
4.5 An approach-based classification of the repositioning of the dragline

An approach-based, classification method was applied to the division of the dragline’s repositioning motives into four categories as follows:

- **Dig:** The dragline repositioned due to a lack of digging materials. This corresponded to a percentage of < 10% of the digging-position that overlapped between two adjacent positions.

- **Spoil:** The dragline repositioned because there was limited spoil-room at a given position. There was a change of dump-height levels in the last 20% of the cycles at a given position.

- **Swing:** Non-optimised swings, such as swings that are hoist-limited, resulted in the repositioning of the dragline. This corresponded to a percentage of > 50% of hoist-limited cycles in the last 20% of cycles at a given position.

- **Others:** Dragline repositions that couldn’t be classified as any of above.

The thresholds were selected based on the analysis of historical data. This method was implemented in MATLAB’s software to classify the different repositioning motives for each relocation-activity.

4.6 Chapter summary

This chapter analysed the dragline benchmark KPIs by using over 200,000 cycles of dragline performance-data, which had been collected from the dragline at Curragh mine during 2012. This analysis contributed to the development of:

1. An automated, block-detection algorithm that used threshold data limits to detect the start-of-dig position in an excavation block. This algorithm has the potential to be adapted and applied to generate performance-summaries for dragline monitoring data collected over individual excavation blocks.

2. An economic cost model that measured operating costs as a function of BCM-degrees by considering equivalent swing angles. This enabled upper and lower, control limits to be established for equivalent, swing-angle charts. It also introduced a new unit of
dragline work (BCM-equivalent degree) that could be used to benchmark the dragline’s performance.

3. Equivalent swing-angle charts, including box and whisker charts for benchmarking the dragline’s swing performance in different, excavation blocks and run-charts to monitor the swing performance of draglines in different locations. The latter can be applied to determine the dragline’s repositioning decisions in order to optimise the dragline’s swing times and dig-sequencing, thus enhancing the productivity of the dragline.

4. An algorithm for classifying the principal operational-motives for repositioning the dragline. This algorithm used a dig-constraint matrix to determine moves in response to a lack of dig material, run-charts of dump heights to determine these moves based on a lack of spoil room, and run-charts of equivalent swing-angles to determine any moves intended to optimise the swing angles.
Chapter 5 The genetic algorithm

5.1 Chapter introduction

The genetic algorithm is capable of progressively generating more favourable results in terms of the defined constraints in order to optimise the dragline’s digging sequencing. The goal programming in this research determined the corresponding and restricted factors, which were a projection of the feasible operations, for the genetic model. Those constraints were, in reality, a reflection of the mine-plan geometry and of other selected benchmarks of the dragline.

At this stage, the purpose of goal programming was to define a series of decision variables and their corresponding constraints, which would reflect the dragline’s actual digging, swinging, and repositioning operations. The determined objective-function was thus used to indicate the dragline’s operational performance in any particular cycle.

To evaluate the dragline’s cycling operation, several constraints were considered as the key elements. These were pertinent to its dig, swing and geometry conditions.

5.2 Defining the constraints

5.2.1 The dig constraints

In the dragline’s digging phase, several KPIs were regarded as keys to its operational performance, and which provided a good basis for the analysis and the modelling. These were:

- The fill time
- The start/end of the fill reach
- The start/end of the fill height
- The drag length
- The fill location
- The payload

### 5.2.2 The swing constraints

In the dragline’s swinging phase, the essential operation performance indicators included:

- The swing time
- The swing angle
- The hoist height
- The payload
- The dump location

The coincidence-curve algorithm was able to classify the cycles into drag, hoist and swing-limited cycles and to statistically imply the cycle dependency, which formed the swing constraints, since hoist-dependent swings were an undesirable operation; these could be a repositioning signal whilst the swing-cost window applied a restriction to the operating swing-angle as another swing-constraint.

### 5.2.3 The excavation-block, geometry constraints

In a real-time operation, certain criteria for the block geometry are maintained to ensure the operational feasibility. These include:

- The dragline’s fill-length and depth
- Its dump-reach and height
- Its positioning steps and distance
- The dimensions of the excavation block

A reasonable range of fill and dump-lengths were thus extracted from the historical data (see Figure 5.1).
In Figure 5.1, the red circle implies the dragline’s fill/dump position. X and Y are the tub-position coordinates referring to the fill/dump-point coordinates, whilst the other colours represent fill-depth/dump-heights. The fill distance between the tub and the dig point thus fell in the range of 20 to 80 metres, whereas that of the dump operation ranged from 70 to 90 metres. Corresponding distances in a certain excavation period were, however, adjusted to meet the specific, fill and dump requirements.

A dragline’s excavation block was thus considered to be 25 metres wide and 30 metres long (derived from collected mine plan data), in favour of the actual operations and relative to the high wall. The number of the dragline’s repositioning within a dig block varied with the pit situation, whilst the step sizes between adjacent positions were usually less than 10 to 15 metres.
5.3 The genetic algorithm’s optimisation of the dragline’s digging sequencing

5.3.1 Overview

The dragline’s dig sequences were unknown in this research and the size of possible representations could have been enormous. An optimisation algorithm was thus needed to progressively construct an optimal dig-sequence. The population of the dragline’s walk sequences and the fitness function of the operation’s performance were required for further optimisation in the genetic algorithm.

The dragline’s tub locations in the different walking sequences were represented by bit strings, which implied that the implementation of encoding, as well as, of decoding were required. In this research, the dragline’s, tub-position coordinates relative to the start-of-block were randomly generated on the basis of the dig and dump locations and were encoded into binary strings as their representations.

The genetic algorithm is equipped with a fitness function, which has the ability to score and to rank the individuals. This fitness function was thus used to evaluate the performance of the individual walking-sequences in this study. This allowed for further progression of the algorithm so as to minimise the cycling times and the swing costs. The fitness function was defined for this research as the objective function that was derived from the development of the goal programming.

The application of genetic changes included crossover and mutation facilitates in order to create new sequences for the further optimisation selection. In the crossover facility (see Figure 5.2), portions of two parents’ walk-sequences from the current generation were combined to create two offspring-sequences. The random subparts of the parent sequences’ bit strings were swapped whilst the start section remained unchanged. In the mutation facility (see Figure 5.3), a mutation point for each selected individuals was randomly chosen for inversion within a feasible range of the reality operation. New walk-sequences for the dragline were thus created for further processing in the algorithm.
A certain fraction of the optimised population contributes to the next generation whilst the rest can be copied intact from the current generation to the next. The selection should be influenced by an individual’s fitness but works probabilistically. Various options have been proposed but the roulette-wheel selection model was preferred for the probability calculation in this thesis. The advantage of this selection model was that every individual in the population had a chance of being selected and this then preserved the diversity (Razali & Geraghty 2011).

The probability of an individual’s walk-sequence being chosen was the ratio between the individual’s fitness and the total fitness in the current generation whereby:

If $f_i$ is the fitness of individual $i$ in the population, its probability of being selected is

$$p_i = \frac{f_i}{\sum_{j=1}^{N} f_j},$$

where $N$ is the number of individuals in the population.

The algorithm of the roulette wheel selection is shown below in Figure 5.4 and the form of the overall genetic algorithm is illustrated in Figure 5.5
The outcome of this stage was a successful generation of optimal, dragline walking-sequence within an excavation block, with their corresponding dig and dump profiles. The optimal solution then considered the operation-time, the swing-cost and the hoist-dependency during the cycling. In combination with start-of-block detection, the genetic algorithm was then able to continue optimising along the excavation blocks until the completion of the
dragline’s operation to a designated pit, as the achievement of a rolling-horizon plan (see Figure 5.6).

Figure 5.6 Dragline walk-sequencing and profiles

(Thornton & Whiten 2003, p.10)

5.3.2 The overall approach

Data over a four-month period was collected from a particular mine pit that had a regular pattern of digging operation. As fill and dump locations had been planned, the genetic algorithm progressively generated the optimised sequences for the dragline’s tub positions.

The following Figure 5.7 illustrates the algorithm’s diagram:

Figure 5.7 The optimisation algorithm diagram
The collected KPIs data-set for the dragline was fed into the algorithm, which was written in the MATLAB software. The start of each excavation block was detected in order to group the dragline’s tub positions, as well as, the information on the other related benchmarks as a position data structure. Under the conditions that were defined by the position data, the dig sequences were initialised as the genetic population. With the calculation of initial fitness for each individual, the genetic process then ran through the entire candidate pool to derive the optimised results.

The detailed algorithm to find the optimal digging sequence of an excavation block is included in table 5.1.

Table 5.1 The optimisation algorithm

```
Algorithm:

// Detect start point of each excavation block

m_block := total block number;
Pt_block := array of start-of-block points;
KPI_dig := dig KPIs;
KPI_dump := dump KPIs;
[m_block, Pt_block] := Start_of_block_Detection (KPI_dig, KPI_dump);

// Process data and run optimization algorithm for each block

for 1: m_block
{
    // Set algorithm constraints
    Ct := constraints of the algorithm;
    L_fill := fill length range;
    L_dump := dump length range;
    b.length := block length;
}
```
\[ bl\text{width} := \text{block width}; \]
\[ d\text{step} := \text{repositioning step distance maximum}; \]
\[ Ct := \text{Construct\_Constraints}(\ L\text{fill}, \ L\text{dump}, \ bl\text{length}, \ bl\text{width}, \ d\text{step}); \]

// Collect input data for each position in a sequence
\[ D\text{pos} := \text{structure of input data at positions}; \]
\[ hwc := \text{high wall crest line}; \]
\[ D\text{pos} := \text{Position\_Data\_Capture}(\ Pt\text{block}, \ KPI_dig, \ KPI\text{dump}, \ hwc); \]

// Run optimization algorithm

// Initialize digging sequences
\[ k := 0; \]
\[ k_{\text{max}} := \text{maximum defined iteration}; \]
\[ P_k := \text{population of } n \text{ randomly-generated sequences}; \]

// Evaluate fitness for each \( i \in P_k \)
\[ F_k := \text{fitness}(P_k); \]

// Run Genetic Algorithm
while \((k < k_{\text{max}})\)
{

// Select unique and fit sequences for the next generation \( k+1 \)
\[ \chi := \text{crossover rate}; \]
\[ p_{\chi} := \text{selected} \ (1 - \chi) \times n \text{ sequences}; \]
Insert \( p_{\chi} \) into \( P_{k+1}; \)

// Perform crossover
\[ p_{\chi\times n} := \text{crossover}(\text{selected} \ \chi \times n \text{ sequences of } P_k); \]
if \(( p_{\chi\times n} \text{ satisfies } Ct )\) Insert \( p_{\chi\times n} \) into \( P_{k+1}; \)
else { repeat this step; }

// Perform mutation
\mu := \text{mutation rate};
\mu \times n := \text{mutation}(\text{selected } \mu \times n \text{ sequences of } \mu_{k+1});
if (\mu \times n \text{ satisfies } Ct ) { \text{ Insert } \mu \times n \text{ into } \mu_{k+1}; }
else { repeat this step; }

// Evaluate fitness for each \( i \in \mu_{k+1} \)
\mu_{k+1} := \text{fitness}(\mu_{k+1});

// Increase iteration
\kappa := \kappa + 1;
}

return sequence from \( \mu_{k+1} \) with max(\mu_{k+1});

5.3.3 The population of the algorithm

In the genetic algorithm, the gene population is usually represented by the binary string for efficient operation. The dragline’s tub positions were, however, collected from GPS, which showed the absolute coordinates relative to a universal standard point. This meant that the figures were larger than were possible with bit-string representations.

To encode the tub positions into binary strings, a reference point for each excavation block was selected as the start-of-block position. A local coordinate system was thus established, where the start-of-block was point (0, 0) and (x, y) of each position within the block was referred to the block’s start-point. Since the size of a digging block was relatively small, converting the coordinates of the tub positions to bit-strings was deemed to be feasible. Apart from the tub positions, the high-wall crest was also converted to a linear function that was
located in the same coordinate system. In Figure 5.8, the tub-position’s coordinate-system dots with a cross-mark represents the tub positions in a particular block; the two lines are the high-wall-crest line and its perpendicular function, respectively; the start-of-block is the reference point (0, 0).

Figure 5.8 The tub-position’s coordinates system

The directions of the draglines’ positioning also varied from the different mine plans. The tub positions relative to the start-of-block were thus not necessarily positive. An extra bit was inserted into the binary string to indicate the signs of a coordinate. By default, 0 was positive and 1 meant negative. The reason why the genes in the genetic algorithm were encoded to binary strings is that they ensure that each individual has fixed size and it is easier to align and modify in order to generate new individual. Real number does not have the flexibility to be modified and performed genetic operation across the candidate pool.

In terms of the generic block-dimensions, tub locations were encoded into two 7-bit binary strings for x and y, respectively. The highest bit was the sign of the number whilst the other 6-bit was the coordinate. Thus x and y were in the range from -64 to +64. Equations 5.1 and 5.2 provide an example of tub position (1, -2):
\[ x = 1 \rightarrow \begin{array}{c}
0 \\
\downarrow \\
+ \text{number}
\end{array} \quad (5.1) \]

\[ y=-2 \rightarrow \begin{array}{c}
1 \\
\downarrow \\
- \text{number}
\end{array} \quad (5.2) \]

5.3.4 The implementation of the algorithm

Prior to the derivation of the actual optimisation algorithm, the start of a digging sequence in each excavation block was detected as the reference point for that block, according to the fill KPIs passed into the algorithm. A data structure to store the related benchmarks information, which examined the geometry-constraints of each digging block, was then established for each position, that is, the:

- Fill location relative to the start-of-block
- Fill length
- Dump location relative to the start-of-block
- Dump length
- Hoist height
- Payload

The direction of the digging sequence was determined by the geographic location of the corresponding, high-wall crest. Algorithm-generated sequences that did not follow this pattern were eliminated from the solutions.

Fill and dump lengths were calculated as the distance between the tub positions and the related fill and dump locations, respectively. Provided that the fill and dump locations are known, defining the range of fill and dump lengths can effectively select tub-positions that are generated by the algorithm and which can meet the geometry requirements of a certain
digging-block. Tub-positions with fill and dump lengths that fall outside the defined range are discarded from the candidate pool.

Generated tub-locations were also subject to the dimensions of the related excavation block. The algorithm removed the sequences that were beyond the range of defined block-lengths and widths. The sequences with two adjacent tub-positions, whose distance were outside the range of the step-size, were also not considered as candidate solutions.

To run the genetic algorithm, the program pre-defined the corresponding parameters as shown below in table 5.2. The parameters were chosen from experiments to give the best performance of the algorithm.

Table 5.2 The GA parameters specifications

<table>
<thead>
<tr>
<th>No. of data bits</th>
<th>Crossover rate</th>
<th>Mutation rate</th>
<th>No. of iterations</th>
<th>Population</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>0.2</td>
<td>0.2</td>
<td>30</td>
<td>20</td>
</tr>
</tbody>
</table>

Twenty digging sequences were randomly generated for the dragline in accordance with the known fill and dump information for each excavation block. Under the conditions of the excavation’s block geometry, a tub-position’s coordinate was encoded into a 7-bit binary string. The total number of blocks in the selected data set was processed in a loop by the algorithm to achieve the rolling-horizon mine-plan, with thirty iterations run through twenty initialised sequences with a crossover and mutation rate of 0.2. The feasibility of each newly-produced sequence was assessed after each iteration in terms of the dig and dump constraints. A roulette wheel selection was the mechanism for developing the candidate pool. A particular dig sequence with the highest fitness score was selected as the candidate for a certain block.
The dragline’s sequencing fitness consisted of both fill and dump constraints (see table 5.3 and table 5.4) as a result of data analysis conducted in Chapter 5.2:

Table 5.3 The GA dump constraints

<table>
<thead>
<tr>
<th>Dump Constraint</th>
</tr>
</thead>
<tbody>
<tr>
<td>70m &lt; Dump reach &lt; 90m</td>
</tr>
</tbody>
</table>

Table 5.4 The GA fill constraints

<table>
<thead>
<tr>
<th>Fill Constraints</th>
</tr>
</thead>
<tbody>
<tr>
<td>20m &lt; Fill reach &lt; 50m</td>
</tr>
<tr>
<td>0m &lt; Block width &lt; 30m</td>
</tr>
<tr>
<td>0m &lt; Block length &lt; 25m</td>
</tr>
<tr>
<td>0m &lt; Step size &lt; 10m</td>
</tr>
</tbody>
</table>

In the calculation of the GA fitness function, the cycles at each tub-position were categorised into hoist and swing dependencies by the coincidence-curve algorithm, and this was followed by the computation of the constraint’s objective function. The total swing-cost of each dragline’s dig sequence was added up according to the calculated, equivalent swing-angle and the swing-cost window in Chapter 4.3.2.

5.3.5 The validation of the algorithm

To test the accuracy and robustness of the algorithm, it was applied to another completely different, digging-sequence data-set as a process for validating the algorithm. The details and results will be discussed in Chapter 6.3.
5.4 The detection of over-digging

Despite optimising the dragline’s repositioning locations, the program also indicated the digging time, which was shown as the number of cycles at each digging location, when the overlap, material percentage of adjacent positions was below a certain threshold (see table 5.5). It was available from the dig constraint matrix (in Chapter 4.4.2), which statistically reflected the status of the over or under-stay digging operation. If the digging-material’s overlap percentage was less than the lower-limit, then the machine should have performed more cycles at its current position before relocating. On the other hand, if the overlap percentage was over the upper limit and over-stay digging was detected, then the repositioning of the machine was required to reduce the digging cost.

Table 5.5 The dig-overlap constraint

<table>
<thead>
<tr>
<th>Dig-overlap Constraint</th>
</tr>
</thead>
<tbody>
<tr>
<td>10% &lt; digging-material overlap percentage &lt; 50%</td>
</tr>
</tbody>
</table>

To reflect the volume of the dig material, each digging position was represented in 3-dimensions (x, y, z). Overlap digging occurred when the difference of each dimension between the two digging positions was below the threshold. The calculation of the digging-material’s, overlap percentage at each tub-position was based on the following equation 5.3:

$$
\eta_{\text{overlap}} = \frac{\text{overlap \_digging \_cycles}}{\text{total \_cycles}}
$$

(5.3)

With planned, fill and dump points, the number of cycles at each tub-position could then be adjusted using the dig-overlap constraint. Under-stay digging resulted in an increasing number of cycles at a particular location, whereas over-stay digging led to fewer cycles being
performed at the same position until the overlap rate fell into the favourable range for the digging.

5.5 Chapter summary
The genetic algorithm process was applied to the historical data over a period of a year with the objective of optimising the dragline’s digging sequences. This aimed at achieving higher fitness scores and lower swing and hoist costs.

Due to the various responses of the block sequences to the defined constraints, there were different levels of relaxation of the constraints required to avoid an infinite loop occurring in the genetic algorithm and to obtain feasible results. Although the principle of ‘the tighter the constraints then the better the results’ applied, adjustments of the fill and dump conditions were possible in order to generate an optimised sequence. The following adjustments or a combination of them were adopted for the following constraints for running the algorithm:

- The dump-reach range between 70m and 90m
- The fill-reach range between 20m and 50m
- The step size less than 10m
- The block dimension with width 30m and length 25m

A trade-off existed between the relaxation of the constraints and the fitness score. Strict constraints were able to favourably duplicate the reality and to reduce any unnecessary factors that might have had a negative impact on the overall accuracy so that a higher fitness score could thus be acquired. The genetic algorithm was, however, effectively limited in response to those restrictions, since a smaller candidate pool may have led to less, individual diversity and to an infinite selection-loop. The solution was to relax the harsh, program conditions to a certain extent, which allowed the genetic algorithm to run smoothly with less compromise in accuracy.

In this case, the dragline’s dig-sequences across a particular pit were optimised by the genetic algorithm under different, block constraints. The best fitness score could thus be achieved for every excavation block to be able to reduce the entire swing and hoist-costs under completely relaxed conditions.
Chapter 6 Results and discussion

6.1 The results

Twelve blocks were excavated on a dragline at the Curragh mine-site in Queensland by a regular, operational pattern and the related results were collected over a four-month period (see Figure 6.1). The red line on the graph represents the corresponding high-wall crest of the digging sequences. The mine plan for the twelve blocks can be seen in Figure 6.2 (blue lines). The magenta points are the dump locations whilst the fill points are marked in green. The digging sequences are the numbered, black lines.

Figure 6.1 The dragline’s original block-digging-sequences with the high-wall crest
In Figure 6.1 and Figure 6.2, a repeated, triangular digging-pattern could be seen in the majority of the twelve excavation blocks. Blocks 6 to 8 did, however, have an irregular pattern when compared to the others in the same strip. This was due to a wet-weather event and to a change of the surface, which did not affect the performance of the algorithm since it was an external factor. Only blocks 1 to 5 and 9 to 11 were thus analysed for optimising the digging-sequences (see Figure 6.3).

Figure 6.2 The dragline’s original, block’s digging-sequences on the mine plan
The following figure 6.4 shows the results of the optimised dig-sequences, which were generated by the genetic algorithm from blocks 1 to 5 and 9 to 11. In this figure, the dash lines were the original dig-sequences of the dragline as performed by the operators, whilst the solid lines were generated automatically by the genetic algorithm with the dig and dump locations as inputs.

Block 2 provides an example for the detailed analysis of the algorithm. The differences between the original dragline’s dig-sequence and the one that was generated by the algorithm can be seen in figure 6.5. Within the same excavation block, the GA-generated sequence tends to be slightly more spread-out for a better balance between the swing and hoist dependency. Figure 6.5 illustrates the dragline’s digging-sequence in block 2.

Figure 6.3 Dragline dig sequences with regular patterns
The optimised dig-sequences of the dragline

Figure 6.4 The optimised dig-sequences of the dragline

The evolution of the genetic algorithm is evident in Figure 6.6 below, where an increasing trend appears in the average fitness scores of the candidate pool for each iteration. During the first fifteen iterations, the fitness scores climb rapidly, whereas a more steady increase can be seen for the second half of the 30 iterations. It shows that the fitness score is converged to a certain optimum. This is a strong indication that sequences with more favourable digging-conditions (that is, with better fitness scores) were selected gradually throughout the implementation of the algorithm. This process is thus quite capable of generating feasible digging-sequences for the dragline.

The comparison of the fitness scores between those of the initial population and those of the last iteration (see Figure 6.7) reflects the progress of this automated procedure. It is obvious that, after the application of the genetic algorithm, the fitness scores are higher and smoother than those at the beginning.
Figure 6.5 The dragline’s digging-sequence in block 2

Figure 6.6 The fitness score of GA in block 2
Another purpose of the genetic algorithm was to reduce hoist-dependency in the cycling operation in order to obtain a cut in the swing costs. A declined tendency appeared on the swing cost during the 30-iteration run in GA. It can be seen in Figure 6.8 that there was a big drop in the first fifteen iterations, whilst the rest had a lower and a more consistent swing-cost.
6.2 Discussion

The goal for the genetic algorithm was to generate optimised digging-sequences for the dragline, which would then have had more favourable dig and swing conditions. This goal was successful in this study as can be seen by the optimisation, which can be seen in this section by comparing the original digging-sequences with those generated by the algorithm.

In figure 6.9, the dragline’s digging sequences, which were generated by the algorithm, achieved the goal of reducing the swing cost (see figure 6.9). It can be observed that the swing costs of blocks 5 and 7 were relatively high. This was because the provided payloads of cycles in those blocks were higher than those of the others. According to the swing cost calculation in equation 3.1, a larger cycle BCM leads to higher, swing costs. The decreased, cost percentages shown in figure 6.10 were thus under control, because all of them lay...
Figure 6.9 Swing-cost comparison

Figure 6.10 The swing-cost, reduction, control chart
between a 3-sigma, upper control limit (UCL) and a 3-sigma, lower control limit (LCL), whilst those in six out of eight blocks lay within a 1-sigma range.

The total cost of the solutions in each excavation block, including the swing and position cost, was reduced when compared to those of the original operator-performed sequences (see figure 6.11).

![Total Cost Comparison](image)

**Figure 6.11 Total cost comparison**

In figure 6.12, the decreasing rates of total sequence costs are within a 1-sigma upper and lower control limit for most of the blocks and all of them lie within a 3-sigma control limit. The total cost-cuts are, thus, strongly controllable.
6.3 Validation of the algorithm

Further validation was necessary for the general application of the algorithm and for an improvement in its accuracy.

In order to test the robustness of the algorithm, another data-set from a different period was applied to the algorithm’s procedure in order to validate the results. This new data-set had a different time-frame and operational pit but shared the same high-wall crest with the old data, under similar, swing-to-dump, cycling operations. The genetic algorithm’s parameters and processes remained unchanged so as to simulate the same optimal environment.

This algorithm has thus been tested on another data-set for a digging-sequence where it also generated reasonable results in optimising the dragline’s digging sequence in each related, excavation block (see figure 6.13).
Figures 6.14 and 6.16 show that the digging sequences, which had been generated by the algorithm, were optimised since both swing and total costs were reduced in each block. In figure 6.15, the swing-cost reductions in most of the sequences were within a 1-sigma upper control limit (UCL) and a 1-sigma lower control limit (LCL) range, whereas only two were in the 3-sigma range. The total cost of the solutions in each excavation block, including the swing and position cost, was also reduced when compared to that of the original, operator-performed sequences. It can be seen in figure 6.17 that the total cost reductions of all sequences fell into the 2-sigma, control limit range. Cost reductions by the algorithm were thus controllably achieved.

Figure 6.13 Dragline digging-sequences in the test data set
Figure 6.14 Test data set swing-cost comparisons

Figure 6.15 Swing-cost, reduction, control chart
Figure 6.16 Test data set total-cost comparison

Figure 6.17 Total-cost reduction control chart
This chapter has presented the results, which were generated by the genetic algorithm, of the optimal digging-sequences of the dragline. It can be seen that these results of the optimisation algorithm are similar to those of original digging-sequences, which were performed by the operators. This was because the constraints that were defined in the algorithm eliminated the sequence-candidates that did not satisfy the constraints and this assured the feasibility of each individual sequence. The algorithm first defined the dimensions of the excavation block based on the corresponding mine plan and the detected start-of-block. Any sequence candidate that fell beyond the block was discarded. The algorithm was then applied using the fill and dump constraints. These were that if the fill length or the dump length of the generated sequence in the algorithm was either longer or shorter than the related range of the constraints, then that sequence would not be treated as a candidate solution. Valid digging-sequences in a particular excavation block also had to have reasonable, positioning steps and distances. The similarity of the digging-patterns thus strongly indicates that the solution that has been provided by the algorithm is feasible in the digging-operation in real-time and will provide the valid paths that the operator can actually follow to finish excavating a particular block.

It was thus determined that the genetic algorithm is capable of optimising the digging sequences of the dragline under certain constraints. These are:

- The dragline’s fill-length and depth
- Its dump-length and height
- Its positioning steps and distance
- The dimensions of the excavation block

Since the genetic algorithm is a search-heuristic and iterative process, the fitness score that is the indicator of the overall performance should thus improve throughout the process. As the results have demonstrated, the fitness score, which was the inverse of the total cost of a sequence, increased along the iterations and tended to be flat at the end where an optimal level had been reached. Similarly, the swing cost of the sequence decreased as the iterations progressed and flattened towards the end. All the solution candidates also had a higher fitness score after the completion of the algorithm than during its initial sequences. This indicates
that the employed algorithm had the unique properties of the genetic algorithm and was thus able to solve the optimisation problem.

The bar charts and the control charts of the swing and the total cost of the digging-sequences, which had been derived from the algorithm, demonstrated that the algorithm had achieved the goal of the optimisation, which was to minimise the operational costs of the processes of swinging and positioning. In the algorithm, the swinging cost was calculated from the developed cost function in conjunction with the equivalent swing-angle that was derived from the coincidence curve, and which had classified the cycle-dependencies into three types: the swing-limited, the hoist-limited and the drag-limited. Hoist-limited cycles should be avoided in order to reduce the swinging cost. On the other hand, the positioning cost was computed as being linear to the positioning distance of the dragline in a certain digging-block. It can thus be seen that the corresponding costs of the sequences from the algorithm had been clearly reduced when compared to those of the original ones. The reduction rate of the cost was also within the 3-sigma control limit, which meant that the decreased cost was reasonable and that it could be achieved in the actual operation.

The algorithm was not only attuned to a particular data set or to a certain scenario, it was also applied to a completely different data-set on a new mine-pit. With the defined constraints, the algorithm was able to provide optimal digging-sequences for the selected excavation blocks with reduced, operational costs for swinging and positioning. As can be seen, the digging-sequences in the validation results have similar digging-patterns to those, which were originally performed by the operator, and which were totally different from the data-set of the analysis. Total swing-costs and the total cost of the optimal sequences in each excavation in the test data-set have been reduced in comparison with the original ones, which were performed by the operator. The reduction rate of the swing-cost was within the 3-sigma control-limit. The cost reduction that was achieved via the process of optimisation was thus reasonable and valid. This can be seen in the validation of the algorithm. The success of the validation implies that the algorithm is capable of solving the optimisation-problem for the dragline's digging-sequences in a given excavation block.
Chapter 7 Conclusions

7.1 Summary

Since the dragline’s repositioning process is a major cause of the loss of productive cycling-hours, considerable skills and judgements are currently required from the dragline’s crew to reposition the dragline for maximum productivity. This thesis investigated the possibility of an automatic optimisation-process for the dragline’s repositioning. It re-examined previous research on the KPIs of the dragline and considered whether these could be suitable indicators of its performance. These KPIs included: cycle-time, cycle-dependency, digging-block dimensions and dig and swing, as well as, dump KPIs. A coincidence curve algorithm, which had been previously developed by this author, was also utilised in this research as a means of classifying the types of cycles as hoist, swing and drag-limited. These KPIs were the fundamental variables that were used in this research to construct a data structure for further analysis on the dragline’s operations including repositioning and digging-sequences.

An analysis of the data that had represented the dragline’s KPIs, in terms of the dragline’s repositioning and digging-sequences, was also undertaken. An automated, block-detection algorithm was successfully developed, which used threshold data-limits to detect the start-of-dig position in any given excavation block. This algorithm was simple but it was effectively adapted and applied to generate summaries for the dragline’s monitoring data, which had been collected for the individual, excavation blocks. It proved to be a useful tool for the constructive data-analysis of the performance of the dragline.

An economic cost-model, which measures the swing-operating costs as a function of BCM-degrees by considering equivalent-swing-angles, was also developed in this thesis. This model enabled the control limits and an optimum range to be established for further analysis of the equivalent-swing-angles and of the performances of the swinging-operation. The cost function was also applied to the data to calculate the swing-costs as part of the objective function in the genetic algorithm. It introduced a new unit for dragline work (the BCM-equivalent degree) that can now be used to benchmark the performance of the dragline.
Equivalent swing-angle charts, including box and whisker charts, which allowed the benchmarking of the dragline’s swing performance in different, excavation blocks, and run-charts were established and examined to monitor the swing performance of draglines in different locations. With the optimum swing-range defined by the cost function, the performance of the swing in each excavation block was visualised in these graphs and then compared. The comparison of the equivalent-swing-angles in the digging-blocks provided valuable feedback, not only on the swing-operations at a particular block, but also on the performance of the operators. It can thus be successfully used to advise them on improving their repositioning decisions in order to enhance the productivity of the dragline.

The principal operational motives for repositioning a dragline were also investigated in this research using a dig-constraint matrix and it was found that these can be automatically classified into four categories - dig, spoil, swing and others, via an approach-based method. The re-positioning moves were determined in response to a lack of dig material and to a change in the level of the dump-height, which determined the repositioning on the basis of a lack of spoil-room; the equivalent-swing-angles could also determine any moves that were intended to optimise the swing-performance by reducing the hoist-limited cycles. An identification of the motives for the repositioning of the dragline was found to be essential for optimising a digging-sequence because it gave a better understanding of where and how the costs and time would be spent. This classification provided the basic knowledge for the development of the objective function in the genetic algorithm.

The digging sequences of draglines are often non-optimal since they are subject to the operators’ judgment. Based on the analysis of the benchmarks in the first part of this thesis, this study has developed criteria that will assist the dragline’s operators in achieving more optimal digging-sequences. This objective was found to be measurable in terms of the increased productivity on a block basis by using a genetic algorithm in conjunction with defined constraints. Those constraints were considered to be the range of fill and dump lengths and the limit of the step-size and block dimensions. A definition of the constraints was necessary for the development of the genetic algorithm. It helped to set up a boundary so that the algorithm was able to search for solutions more efficiently and, thus, to more effectively converge on the optimum results. This not only increased the efficiency of the
computation, but also derived optimised results that were feasible and which were able to be used in the actual operations.

This algorithm adapted the sequences of the tub-positions of the dragline in each excavation block as the individual candidates, which were then the sequences, which needed to be optimised by the algorithm. It took the dragline’s swing costs, which happened to be the most important motive for the dragline’s repositioning, and the position cost, which was the major loss of the time in the dragline’s operation, into account as the objective function. A digging-sequence was thus derived in each excavation block for that swing-to-dump cycling, which then met the goal of minimising the operational costs. A genetic algorithm was deemed to be successful if its results lead to higher fitness scores and, in this case, to lower, defined operational-costs when compared to the scores of the original and initial candidates.

To ensure the flexibility and robustness of the algorithm, the optimisation solution was demonstrated and tested through two series of dragline digging-blocks at different periods of times. For both data-sets, the algorithm generated feasible results with a lower cost when compared to the original, operator-performed digging-sequences.

By comparing the new, optimised digging-sequences with the corresponding, original digging-sequences, the operators can then be informed of how to improve the repositioning of the dragline in any given excavation block. This includes:

- The positions where the dragline stands for cycling can achieve more favourable dig and swing, which can lead to lower operational-costs.
- Knowing when to move the dragline can avoid the negative impacts resulting from a lack of digging-material, from a lack of spoil-room or from non-optimised swings.

This research has potentially provided an important tool for advising the operators on how to improve the dig sequences of a dragline in an excavation block. It could thus be implemented as an operator’s assistant. This algorithm potentially represents a step forward in the automation of a dragline.
7.2 Re-evaluating the research questions

As discussed in Chapter 1, the important research questions for this thesis were:

- What are the motives for the dragline operators’ decisions to reposition the draglines during the excavation of the block and is it possible to automatically classify these on the basis of monitored data?
- Can a back-analysis algorithm be developed to optimise the repositioning decisions so as to minimise the overall swing and positioning costs?

This thesis was able to determine the motives of the dragline operators during the excavation of the blocks. These motives were determined to be:

- Dig - where the dragline repositions due to a lack of digging materials.
- Spoil - where the dragline repositions because there is limited spoil-room at a given position.
- Swing - where non-optimised swings, such as swings that are hoist-limited, result in the dragline’s repositioning.
- Others - where the dragline’s repositioning decisions cannot be classified as any of the above.

The repositioning-motives for the digging implies that the operators have to relocate the dragline if there are not enough digging materials in the current digging-position. This can be measured as the percentage of overlapped materials between two adjacent, digging-positions in a digging-sequence. If the rate of the overlapped materials is less than 10%, then there is a lack of digging-material at the current tub-position; the repositioning of the dragline is thus required to continue the excavation of the block. With the calculation of the dig-matrix (as discussed in Chapter 4.4.2), the percentage of the overlapped materials in two adjacent positions can thus be effectively quantified on the basis of collected data. This provides a computational algorithm that indicates that the lack of digging-materials is one of the most important motives for the repositioning of a dragline.
Another motive for the repositioning of the dragline can be categorised as the limited spoil-room at a given tub-position of the dragline. Since most of the waste-materials would be dumped into a designated spoil-area and if the spoil-room has reached its limit, then the repositioning of the dragline would be necessary for waste-materials to be able to be dumped into a new spoil-room. The most effective factor in monitoring the spoil-room was found to be the dump-height of the operational cycles. If there is a large change in the level of the dump-height at the end of cycling in a particular position, it is most likely that the amount of dumped materials in the spoil-room has reached its maximum and therefore, that a repositioning of the dragline is required to continue the operation. The dump-heights of the dragline’s cycles is therefore, also one of the important KPIs for evaluating the performance of the dragline, which was analysed in the coincidence curve algorithm as discussed in Chapter 3.3.

The repositioning of the dragline could also be triggered by non-optimised swings. This required reference to the hoist-limited cycles, which were classified by the coincidence curve algorithm. If a large number of hoist-limited cycles occur at the end of the cycling-operation in a certain digging-position, then repositioning should be considered since these long-hoist, short-swing cycles impose a large strain on the machine and will slow down the entire cycling-process. A non-optimised swing is the most important motive for the repositioning of the dragline amongst those three discussed above. Whilst it is not as straight-forward as the others, it has a larger impact on the productivity of the machine as well as on the machine itself. Therefore, this thesis focused on optimising the repositioning of the dragline with minimum swing-costs.

This research has also developed the genetic algorithm to back-analyse the optimisation of the repositioning decisions and to generate optimal digging-sequences for the dragline in each excavation block with minimal swing and positioning costs. This back-analysis approach was implemented because the algorithm was run on the basis of the provided dig and dump data.

That data was also used to define the constraints of the algorithm, which were as follows:

- The fill-reach range (between 20m and 50m) - where the range of the fill length was defined to ensure that the generated results could be used in the actual
operation. This range effectively disregarded those sequences, which had fill lengths falling outside the limits.

- The dump-reach range (between 70m and 90m) - where the range of the dump length was set to achieve a feasible outcome; any generated tub-position, which required a dump-length that was beyond this range, was eliminated.

- The step size (less than 10m) - where a limit was set on how far the dragline could move from one position to another.

- The block dimensions (width 30m and length 25m) - where the boundary of a particular block was defined and so the sequences that were generated by the algorithm were guaranteed to be in the corresponding, excavation block.

The genetic algorithm was thus able to provide solutions even though the optimum digging-sequences were unknown and despite the fact that there would be hundreds of thousands of possible solutions in one excavation block. It was also capable of effectively converging upon the global, optimum results. In this thesis, the sequences of tub positions in each excavation block were the candidates of the genetic algorithm; whereas the costs associated with the swing and position were the objective function. The cost function, which was developed in Chapter 4.3.2 in conjunction with the calculation of the equivalent-swing-angle (see Chapter 4.3.3), provided a method for the computation of the operational swing-costs. This straightforward calculation assisted the algorithm in successfully converging upon the optimised solutions during the iterative process.

The validation and discussion sections in Chapter 6 demonstrated that this algorithm was able to effectively suggest an optimal digging-sequence with reduced swing and positioning costs. It also had the robustness and flexibility to be applied to different data-sets. The significance of this research is that this algorithm can thus be successfully used to analyse a dragline-operator’s performance and to improve that operator’s repositioning-decisions.

7.3 Limitations of this research
The algorithm was usually able to generate feasible, dig-sequences for the dragline. A limitation was, however, that if block dimensions changed appreciably or if material characteristics influenced the swell factors, then the spoil constraints would need to be reset. Currently, once the constraints were set up on a strip, then the algorithm optimised the digging-sequences of all of the excavation blocks.

The algorithm that has been developed in this study also requires accessible data in order to be able to generate optimal digging-sequences. In other words, it was not able to predict the optimal solutions and to advise operators in advance on how to reposition the dragline. Instead, it is a tool for operator training.

7.4 Recommendations for further research

In this research, the implementation of the genetic algorithm required input data for the dragline’s digging and dumping history. This was for the purposes of back-analysis rather than for predictions. A more realistic and practical method would be to give the operator more flexible feedbacks in real-time on how to reposition the dragline with only minimal, operational costs during the digging-sequences of any particular, excavation block. It is thus recommended that a more advanced method should be developed and implemented by future researchers, which would simulate and better optimise the fill and dump operations of the dragline at each tub position in the digging-sequence. By combining a real-time data-analysis of the dragline’s repositioning with the genetic algorithm to optimise the digging-sequences as developed in this thesis, further research may then lead to the development of more useful, feedback tools for the operator and to the future automation of the dig-sequencing plans for draglines.
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Glossary

Open-pit mining
Open-pit mining, or open-cast mining is a surface mining technique of extracting rock or minerals from the earth by their removal from an open pit or borrow. Open-pit mines are used when deposits of commercially useful minerals or rocks are found near the surface; that is, where the overburden (surface material covering the valuable deposit) is relatively thin or the material of interest is structurally unsuitable for tunneling (as would be the case for sand, cinder, and gravel).

Dragline
A dragline excavator is a piece of heavy equipment used in civil engineering and surface mining. Draglines fall into two broad categories: those that are based on standard, lifting cranes and the heavy units that have to be built on-site. Most crawler cranes with an added winch drum on the front can act as a dragline.

Sequencing (dragline)
The operational process of moving a dragline through a number of positions to excavate a block in a generic block-to-spoil-type of mining operation is often referred to as sequencing.

Genetic algorithm
In the field of artificial intelligence, a genetic algorithm (GA) is a search heuristic that mimics the process of natural selection. This heuristic (also sometimes called a metaheuristic) is routinely used to generate useful solutions to optimization and search problems. Genetic algorithms belong to the larger class of evolutionary algorithms (EA), which generate solutions to optimization problems using techniques inspired by natural evolution, such as inheritance, mutation, selection, and crossover.

Crossover (genetic algorithm)
In genetic algorithms, crossover is a genetic operator used to vary the programming of a chromosome or chromosomes from one
generation to the next. It is analogous to reproduction and biological crossover, upon which genetic algorithms are based. Cross over is a process of taking more than one parent solutions and producing a child solution from them.

**Mutation (genetic algorithm)**

Mutation is a genetic operator used to maintain genetic diversity from one generation of a population of genetic algorithm chromosomes to the next. It is analogous to biological mutation. Mutation alters one or more gene values in a chromosome from its initial state. In mutation, the solution may change entirely from the previous solution. Hence GA can come to better solution by using mutation.

**Fitness function (genetic algorithm)**

A fitness function is a particular type of objective function that is used to summarise, as a single figure of merit, how close a given design solution is to achieving the set aims. In particular, in the fields of genetic programming and genetic algorithms, each design solution is commonly represented as a string of numbers (referred to as a chromosome). After each round of testing, or simulation, the idea is to delete the 'n' worst design solutions, and to breed 'n' new ones from the best design solutions. Each design solution, therefore, needs to be awarded a figure of merit, to indicate how close it came to meeting the overall specification, and this is generated by applying the fitness function to the test, or simulation, results obtained from that solution.

**Layer cutting (dragline operation)**

When operating conditions permit excavation of the dig-out from one position over the high-wall, the dragline generally excavates the dig-out in layers. The key cut is formed, one layer at a time, by excavating along the high-wall before the completion of each layer.
Discount factor (dragline operation)

A percentage discounted from the walking speed of the dragline to estimate the time spent in repositioning the dragline. (The greater the digout length, the less walking time will be required per panel. Repositioning in the digout can affect cycle time. Therefore, walking patterns must be considered when selecting digout length. Time spent in repositioning the dragline can be estimated by discounting the walking speed of the dragline.)

Labour burden (dragline operation)

Labour burden means fringe benefits. It usually consists of the following: 1) statutory burden: this includes items mandated by law, such as the employer’s contribution to Social Security, Workmen’s Compensation Insurance, Unemployment Insurance, and other costs that result from government action; 2) Benevolent Labour Burden: These are the items that an employer must pay to be competitive in the labour market to keep capable people. These include health insurance, group life insurance, pension plans, and other items directly related to wages and employment; 3) Union Enforced Burden: This includes items that may be the result of direct union negotiation.
Appendix A: The summary of the algorithm in MATLAB

%% Start of block detection
[start_of_bls] = StartOfBlock(activity_steps,tub_e,tub_n,start_fill_height,5);
hold on
[pos_ind,pos_cyc_ind,steps] = DLPosition(tub_e,tub_n,activity_steps,5);

%% Dig sequence data capture and Genetic Algorithm
BL_NUM = length(start_of_bls);
BIT = 7;
POP_SIZE = 20;

Fitness = zeros(Pop_SIZE,BL_NUM);
Swing_cost = zeros(Pop_SIZE,BL_NUM);
Pos_cost = zeros(Pop_SIZE,BL_NUM);
Fill_lengths = zeros(Pop_SIZE,BL_NUM);

F_before = zeros(Pop_SIZE,BL_NUM);
S_before = zeros(Pop_SIZE,BL_NUM);
P_before = zeros(Pop_SIZE,BL_NUM);
Fill_before = zeros(Pop_SIZE,BL_NUM);
% Swing cost function

cost_data = struct('degree',degrees,'cost',cost_BCM_degree);

% Data process for each excavation block

for bl_num = 1:12

    % set algorithm constraints
    
    constraints =
    struct('f_len_min',20,'f_len_max',50,'bl_length',20,'bl_width',30,'step_len',10,'d_len_min',70,'d_len_max',90,'bl_range_params',[1 1.5*30 -5]);

    %constraints =
    struct('f_len_min',25,'f_len_max',40,'bl_length',30,'bl_width',15,'step_len',10,'d_len_min',70,'d_len_max',90,'bl_range_params',[1 3 -2*15]); %test

    % Retrieve data at each dragline tub position

    [dig_data,dump_data,swing_data,pos_size,start_block] = 
    PositionData(start_of_bls,pos_cyc_ind,bl_num,tub_e,tub_n,fill_e,fill_n,start_fill_height,dump_e,dump_n,hoist_h,payload);
    [hw] = HighWall(hwc,start_block);

    figure(5);
    hold on

    plot_x = start_block.easting-100:start_block.easting+100;
    plot(plot_x, hw.k*(plot_x-start_block.easting)+hw.b+start_block.northing, 'r');

    % Initialise dig sequences and calculate their fitness as well as productivity
tic
[seq_X,seq_Y] = IniDLSequence(dig_data,dump_data,pos_size,hw,start_block,POP_SIZE,BITS,constraints);
toc

for i = 1:POP_SIZE
    X = SeqDecode(seq_X(i,:),BITS);
    Y = SeqDecode(seq_Y(i,:),BITS);
    [F_before(i,bl_num),S_before(i,bl_num),P_before(i,bl_num), Fill_before(i,bl_num)] = DLFitness(X,Y,dig_data,dump_data,swing_data,pos_size,start_block,degrees,cost_BCM_degree);
end

% Genetic Algorithm

ga_data = struct('crossover',0.2,'mutation',0.2,'iteration',40,'bits',BITS,'population',POP_SIZE,'position',pos_size,'seqX',seq_X,'seqY',seq_Y);

[Px_curr, Py_curr, F, swing_cost, pos_cost, fill_length_tot] = GARun(ga_data, dig_data, dump_data, swing_data, cost_data, hw, start_block,constraints);

% Display results
Opt_seq_x = zeros(BL_NUM,pos_size);
Opt_seq_y = zeros(BL_NUM,pos_size);
[max_f, IX] = max(F);
Swing_cost(:,bl_num) = swing_cost;
Pos_cost(:,bl_num) = pos_cost;
Fitness(:,bl_num) = F;
Opt_seq_x(bl_num,:) = SeqDecode(Px_curr(IX,:),BITS);
Opt_seq_y(bl_num,:) = SeqDecode(Py_curr(IX,:),BITS);
Fill_lengths(:,bl_num) = fill_length_tot;
[ cyc_num_repos, cyc_num_repos_prev ] = IsReposition( dig_data,pos_size );

figure(1);
hold on
SequencePlot(POP_SIZE,BITS,Px_curr(IX,:),Py_curr(IX,:),start_block, 1, '-'), 2,'final');
OriginalSeqPlot(bl_num, start_of_bls, pos_cyc_ind, pos_size, tub_e, tub_n, 1, ':', 2);
legend('GA Generated Sequences', 'Operator-Performed Sequences');

% high wall crest plot
plot_x = start_block.easting-50:start_block.easting+50;
plot(plot_x, hw.k*(plot_x-start_block.easting)+hw.b+start_block.northing, 'r');

[ Original_fitness, Original_swing_cost, Original_pos_cost, Original_Fill_length_tot ] =
OriginalFitness( dig_data,dump_data,swing_data,pos_size,start_block,degrees,
cost_BCM_degree );
WriteOutputs( 'C:\Users\apple\Google Drive\M.Phil Work\Results\GA_Outputs',
Original_fitness, Fitness(IX,bl_num), Original_swing_cost, Swing_cost(IX,bl_num),
Original_Fill_length_tot, Fill_lengths(IX,bl_num), cyc_num_repos, cyc_num_repos_prev, bl_num );

end